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OXIDATION AND ENRICHMENT IN THE SAN MANUEL COPPER DEPOSIT, ARIZONA.[1]

G. M. SCHWARTZ.

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ABSTRACT.

The San Manuel copper deposit of southwest Arizona was discovered by drilling done under the strategic-minerals program of the United States Government. The ore is disseminated throughout a large zone in quartz monzonite (Oracle granite) of Precambrian age and monzonite porphyry of Tertiary (?) age. Oxidation and enrichment have played an important part in development of present conditions within the deposit.

The oxidation and enrichment took place during an erosion cycle that preceded the present cycle and probably the last two cycles. A conglomerate, here referred tentatively to the Gila conglomerate, was laid down on the eroded and oxidized ore deposit; in some places the conglomerate reaches a thickness of over 1,000 feet and perhaps much more. The age of the Gila conglomerate is believed to be late Pliocene and possibly Pleistocene, but solution of the problem of the correlation of the conglomerate in

[1] Published by permission of the Director, U. S. Geological Survey, and presented before the Society of Economic Geologists, San Francisco, February, 1949.

the San Manuel area requires detailed work over a large area. Extensive tilting and faulting followed the deposition of the conglomerate. Alluvial slope gravels were laid down across the eroded edges of the conglomerate, and later faulting affected both gravels and conglomerate.

The zones of oxidation and enrichment are not related to the present water table. The depth to the bottom of the oxide zone ranges from 285 feet to 1,630 feet. Differences in surface altitudes and probably tilting of the original oxide zone account for the great differences in depth.

Chrysocolla is the most important copper mineral in the oxide zone, which contains tens of millions of tons of low-grade material averaging about 0.70 percent copper.

Sulphide enrichment was variable. In general the increase in copper content averages only a few tenths of a percent. Some holes in the eastern part of the area show a relatively thin zone that was enriched fairly heavily. An unusual feature is the presence of considerable disseminated native copper and goethite in the sulphide zone.

INTRODUCTION.

DRILLING has been in progress on the San Manuel copper deposit since 1943, but little detail has been published regarding this unusual deposit. Oxidation and enrichment have played an important rôle in the development of parts of the deposit as it now exists. Inasmuch as considerable time must elapse before the surrounding area can be mapped and a detailed report prepared, it is desirable to make available a digest of information regarding secondary changes. A previous report [2] gives a general summary of the geology and it would be helpful to refer to this for background data. A summary of the geology has also been published by Steele and Rubly [3] and by Chapman.[4] Peterson [5] has described the adjacent area and the Mammoth-St. Anthony mine. Lovering [6] has recently published an analysis of geothermal gradients obtained in several of the drill holes.

In July 1944 the writer was assigned by the U. S. Geological Survey to carry forward geologic investigations in connection with the drilling of the San Manuel deposit. These geologic studies were carried on at first in cooperation with the U. S. Bureau of Mines during their exploratory drilling program (Project 1466) and later with the Magma Copper Company and the San Manuel Copper Corporation as commercial development of the deposit proceeded. The list of individuals to whom the writer is indebted is long. J. H. Hedges and T. L. Chapman of the U. S. Bureau of Mines; Philip Kraft, Wesley P. Goss, H. J. Steele, G. R. Rubly and H. I Ashby of the Magma Copper Company; E. N. Reed and Donald Gill of the Inspiration Consolidated Copper Company; Professor B. S. Butler of the University of Arizona; D. H. Kupfer,

[2] Schwartz, G. M., Geology of the San Manuel area, Pinal County, Arizona: U. S. Geol. Survey, Strategic Mineral Investigations, Preliminary Maps 3–180, 1945.

[3] Steele, H. J., and Rubly, G. R., San Manuel prospect: Mining Technology 11, A.I.M.E. Tech. Pub. no. 2255, Sept. 1947.

[4] Chapman, T. L., San Manuel copper deposit, Pinal County, Arizona: U. S. Bur. Mines, Rept. Inves. 4108, 1947.

[5] Peterson, Nels P., Geology and ore deposits of the Mammoth Mining Camp area, Pinal County, Arizona: Arizona Bur. Mines, Bull. 144, Geol. Ser. No. 11, 1938.

[6] Lovering, T. S., Geothermal gradients, recent climatic changes, and rate of sulphide oxidation in the San Manuel district, Arizona: ECON. GEOL. vol. 43, pp. 1–19, 1948.

Ralph S. Cannon, Jr., and G. H. Espenshade of the U. S. Geological Survey all deserve credit for generous cooperation Some of the early laboratory work was done at the University of Arizona, but the greater portion at the University of Minnesota. The writer is indebted to both institutions. Finally, T. S. Lovering and John R. Cooper of the Geological Survey read the manuscript and made suggestions for its improvement.

SUMMARY OF GEOLOGY.

General Statement.—The San Manuel copper deposit is located one mile south of the Mammoth-St. Anthony mine at Tiger, Arizona, about 40 miles northeast of Tucson, and 25 miles south of the large disseminated deposit at Ray. The site is on the west side of the San Pedro River where the pediment of the Black Hills emerges from the alluvial slope deposits of the San Pedro Valley. The Black Hills appear to be a long northward-projecting spur of the Santa Catalina Mountains. Arizona State Highway No. 77 passes through the explored ground, but a new route is being surveyed in order to avoid the ground soon to be developed.

The area is in the midst of the Basin and Range province of southern Arizona. Within a radius of 100 miles lie such well known Arizona copper districts as Ray, Bisbee, Morenci, Globe, Miami, and Superior, and within 200 miles are Jerome, Bagdad, and Ajo.

The climate is arid, and the water table lies at considerable depths except in the valleys. As a consequence deep oxidation is the rule, although depth of oxidation at San Manuel is not related to the present water table. The water level in the drill holes ranges from about elevation 2,450 to 2,950. This is at depths of 300 to 800 feet, but the common depths are between 500 and 600 feet. The top of the zone of enrichment in the copper deposits does not correspond with the present water table.

Areal Geology.—Relatively few rock formations are exposed in the immediate vicinity of the drill holes. Within an area of 9 square miles that has been mapped on aerial photographs the number of outcrops is relatively small. The rocks exposed in the immediate area, from oldest to youngest, consist of quartz monzonite (Oracle granite) and aplite, monzonite porphyry, diabase, Gila (?) conglomerate which includes some flows and tuffs, felsite, felsite breccia, the alluvial slope deposits of the San Pedro Valley and Recent alluvium in the dry washes.

The quartz monozonite is part of a Precambrian granitic mass which occupies a large area on the north slope of the Santa Catalina Mountains and is commonly known as the Oracle granite.[7] The unaltered rock is a light-pink coarse-grained, porphyritic rock, liberally spotted with biotite. Fine-grained aplite dikes cut the coarse-grained porphyrite rock on Red Hill and in some of the drill holes.

The quartz monzonite has been intensely affected by hydrothermal alteration in the area of exploration and northward to Tiger. Locally it has been

[7] Peterson, Nels P., op. cit., p. 8.

impregnated by copper minerals. Much of the western portion of the ore body is in quartz monzonite as is also the deepest ore of the eastern part.

Monzonite porphyry of Tertiary (?) age occurs as irregular intrusions in the quartz monzonite and is the predominant rock in the eastern portion of the area. The porphyry is much finer grained than the quartz monzonite and is easily distinguished from it in outcrop, and, as a rule, in drill cuttings. The composition is not radically different from the quartz monzonite although the porphyry has less quartz and it is confined to the matrix. The alteration and mineralization were similar to that in the quartz monzonite, and drill holes crossing from one to the other normally show no deviation in copper content.

Small fine-grained diabase dikes cut the quartz monzonite and monzonite porphyry. They are fairly numerous and are mineralized like the older rocks, but make up only a small percentage of the total rock. Diabase dikes have been cut by many drill holes. Diabase is rare in the eastern part of the ore body. A sizable diabase dike was encountered in the most westerly drilling. Although the magnitude of the dike cannot be well established, there are indications in drill holes in the area that it may be 100 feet or more in width and have a strike length in excess of 800 feet. It was intersected in holes 76, 60, 74, 47, 46 and 64.

Cutting the preceding rocks are dikes and probably irregular intrusions of felsite and felsite breccia. The felsite is a very fine-grained, cream and light-gray colored rock with a few small feldspar and quartz phenocrysts in a finely crystalline groundmass. The felsite was intruded after mineralization took place, although it does contain some very finely divided pyrite. Assay values are consistently low in the felsite and the values recorded are believed to be a result of contamination from above. At the surface this felsite has a very light-pink color resulting from oxidation of finely disseminated pyrite. Volcanic rocks older than the felsite are abundant north of Tiger.

The main outcrop of the copper-bearing rock consists of a small triangular area, roughly $350 \times 400 \times 500$ feet. Two other small exposures lie to the east of the main outcrop of the ore near the E-W zero line of the drill grid and the remainder is buried beneath conglomerate and later alluvial material (Fig. 1). The conglomerate was mapped by Peterson [8] as the Gila conglomerate, and consists of a complex deposit of alluvial material, interbedded with lava flows and tuffs and volcanic breccias. The conglomerate dips from 30° to 35° northeast in the vicinity of the San Manuel deposit. North of Tiger steeper dips have been observed. The conglomerate is barren except at a few places where it is believed that supergene solutions have deposited small amounts of chrysocolla and malachite. The alluvial slope deposits of the San Pedro Valley lie unconformably on the conglomerate and dip about 5° east toward the river. The conglomerate and alluvial slope deposits have been extensively dissected because the San Pedro River has entrenched itself in the earlier deposits of its valley.

Structure.—The structure of the San Manual area is complex and difficult to work out because most of the drilling has been in massive igneous rocks which furnish no guide as to amount of tilting, offset and so on.

[8] Peterson, Nels P., op. cit., p. 15 and plate 1.

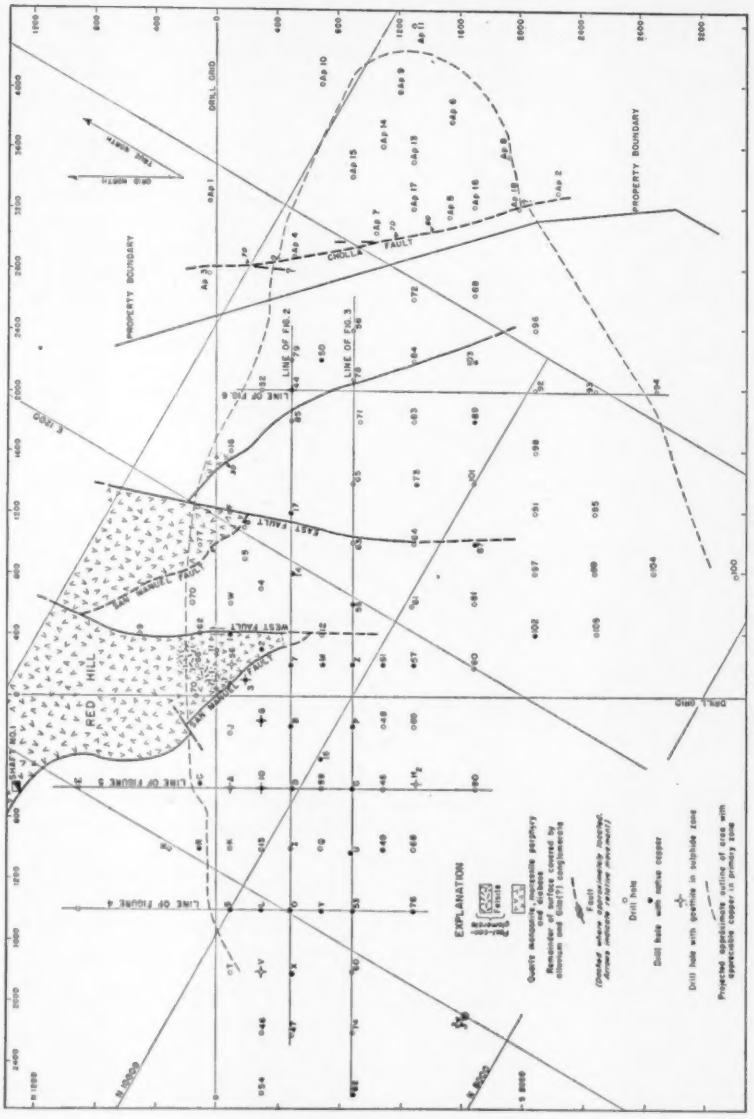


FIGURE I.—SKETCH MAP OF SAN MANUEL AREA

Surface altitudes range from 2,975 to 3,440 feet

In general, the quartz monzonite and monzonite porphyry are so complexly and intimately related that it is usually impractical to correlate the individual masses from hole to hole. The dikes and irregular intrusions of diabase and felsite likewise reveal no common pattern. Commonly, however, the porphyry lies above the main mass of the quartz monzonite, particularly in the eastern part of the area drilled.

The only bedded consolidated rock in the area is the Gila (?) conglomerate which has been extensively tilted and deformed. The prevailing strike is northwest and the dip is northeast at an angle rarely less than 25° or greater than 45° although in nearby areas dips of 60° have been mapped.

Numerous faults cut the Gila (?) conglomerate and underlying rocks. It is probable that the faults mapped are only a small part of the existing faults. In drilling, caving-gouge zones are fairly common and radical differences in the

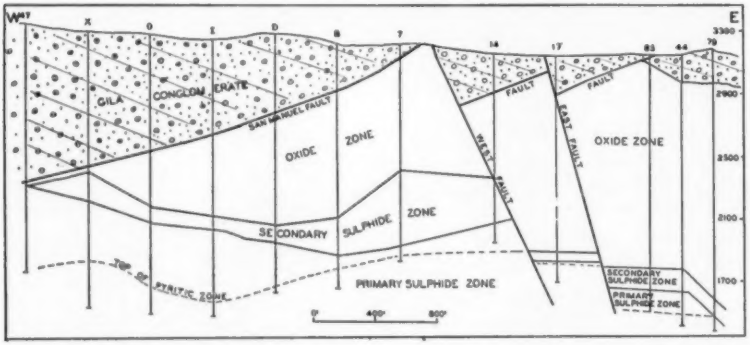


FIG. 2. Longitudinal section of San Manuel Copper Deposit along S 500 of drill grid.

altitude of the top of the sulphide zone from hole to hole suggest faults, some of considerable displacement. There is some evidence that the Mammoth fault extends into the San Manuel area from the Mammoth-St. Anthony mine where it is well known. The fault is poorly exposed, but the straightness of the contact of the Gila (?) conglomerate with the underlying rocks, in spite of irregularities in the topography, indicates the presence of the fault and that its dip is steep. Within the area of drilling a fault, which lines up with the Mammoth, is exposed in the Gila (?) conglomerate just east of holes 63 and 87, and was named the East fault by Steele and Rubly.[9]

Another and more important fault, named the San Manuel fault, occurs along the southwest side of the largest of the exposed mineralized areas. This is clearly exposed in exploration pits and dips 32° southwest. It flattens somewhat to the west. The dip of the beds is opposite to the direction of dip of the fault plane, so there is little doubt of the contact being a fault.

[9] Steele, H. J., and Rubly, G. R., op. cit., p. 3.

Probably the best marker for determination of the location and effect of faults is the bottom of the Gila (?) conglomerate which, over much of the area, is the San Manuel fault plane. Once the general picture of the step faulting to the east by the West fault and East fault was established, the bottom of the conglomerate could be quite accurately predicted in subsequent drilling within the fault blocks.

A fault forms the east contact of the main exposed copper-bearing area, and has been named the West fault by Steele and Rubly. Where exposed in a shaft near hole 9, it dips 60° east. This fault is believed to offset the southeastward extension of the San Manuel fault nearly 1,500 feet to the northwest as shown on Figure 1.

To the east of the Mammoth fault is a nearly parallel fault that has been named the Cholla fault by the staff of the exploration companies. This fault is well exposed just northeast of the concrete bridge on Highway No. 77. Here the tilted Gila (?) conglomerate is upthrown adjacent to the very gently dipping alluvial slope gravels of the San Pedro Valley. Drill logs indicate a vertical displacement of nearly 800 feet with the east side downthrown. This fault proves that some of the faulting in the area is of a very recent date.

THE ORE DEPOSIT.

Structure.—The form of the ore body or ore bodies is only imperfectly known. Vertical churn drill holes into an ore deposit beneath a thick layer of conglomerate do not furnish adequate data on details of the structure. 122 holes have been drilled in the deposit by the Bureau of Mines and two companies involved, but the area is so large that at places the spacing is wide. The mineralized rock is remarkably uniform in copper content. For example, the primary ore in one hole extended from 705 to 2,160 feet. The average copper content for the 1,455 feet was just over 0.9 percent; one five-foot section assayed 2.66 percent, but otherwise the maximum assay was 1.47 percent, and the minimum assay was 0.62 percent; most of the assays fell between 0.75 and 1.10 percent.

There are few sharp contacts of ore with lean rock. Normally one grades into the other, and any boundary must be drawn arbitrarily on the basis of an assay value. In the work of the U. S. Geological Survey no attempt was made to select zones or define ore outlines in terms of commercial values. Instead, an attempt was made to outline the ore bodies and the zones within the ore body in terms of the character of mineralization. For example, the footwall of the ore in most of the early drilling was a highly pyritic material. The gradation into this pyritic zone was relatively sharp but, even so, extended over many feet. For defining this boundary a general figure of 0.3 percent copper was used. For showing the nature of the mineralization, this was better than a higher cut-off that would be used to define commercial ore.

In outlining the oxide, supergene sulphide, and hypogene sulphide zones, mineralogy, especially as aided by study of polished mounted concentrates, was used. Here too, there was much leeway and considerable personal judgment entered into the final result. The problem of drawing some sort of contact be-

tween the oxide and supergene sulphide zone was particularly difficult. In general the bottom of the oxide zone was drawn where visual examination and oxide copper assays indicated a decidedly subordinate amount of oxidized minerals as compared with the amount of residual sulphide.

The bottom of the supergene sulphide zone was placed at the point in any given drill hole where chalcocite essentially disappeared in the cuttings. Much of the lower part of the supergene sulphide zone shows little enrichment.

The deposit as a whole, regardless of whether oxidized, enriched, or primary, can best be described in terms of its western and eastern portions as developed on a drill grid with its long axis in a direction North 60° 10′ East. The first holes drilled by the Bureau of Mines (Fig. 1) were in the vicinity of the outcrop of the ore and near the middle of the north side of the ore body as

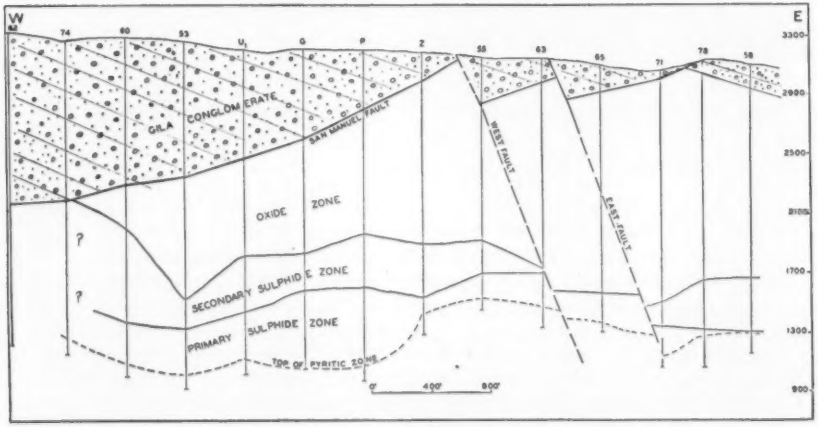


FIG. 3. Longitudinal section of San Manuel Copper Deposit along S 900 of drill grid.

now known. From about 1,200 east on the drill grid, which is near the supposed extension of the Mammoth fault, westward to 2,600 west on the grid, is the western * ore body. This is a comparatively regular tabular zone of copper ore. The zone averages about 400 feet in thickness and dips southward on the grid generally, from 50° to 60° (Figs. 4 and 5). Geographically the dip would be in a direction approximately S. 30° E. The footwall rock is highly pyritic and is represented at the surface by the red, iron-stained rocks of Red Hill. The top of the pyritic zone below the western ore body, using a 0.3 percent copper content as a boundary, is a remarkably regular surface. The ore zone extends beyond the deepest holes (2,750′) drilled in this area. The copper content becomes low toward the west end of the area drilled, and for the present this may be considered as the west end of the ore body.

* In a recent prospectus the company has referred to this as the northern ore body.

The hanging wall of the copper ore body is gradational and more indefinite than the footwall. The typical hanging rock is a moderately altered facies of monzonite porphyry or quartz monzonite, characteristically dark gray in color because of the presence of abundant biotite. The contact with the ore is complicated by oxidation and enrichment, but consideration of the character of the rock and of assay values resulted in a fairly satisfactory boundary. Here too, copper values less than 0.3 percent were used as a cut-off. As shown by the cross-sections there is a fair accordance between hanging wall and footwall in the western ore body. In the early drilling considerable faulting and lean ground was encountered in the vicinity of east 1,200 on the grid. Hole 8 of the Bureau of Mines seems to have followed a fault zone for most of its length. A later drill hole to the east, on the east 2,000 drill grid coordinate, showed that ore occurred beyond the zone of faulting. Following out this lead, other holes were drilled farther south and developed what is obviously the most important part of the deposit, the east ore body. The continuity of the east ore body with the west ore body is well established although in mining it may have to be considered essentially a separate ore body.

The character of the mineralization in the east area is like that of the west area, but the form of the deposit is very different. In the northeastern part of the east area the pyritic zone swings somewhat southward, and accordingly there is little ore down to coordinate south 300. Southward along east 2,000 the drill holes show that the moderately altered hanging wall rocks, so characteristic to the west, are lacking and the pyritic mineralization seems to have affected the rock over the ore. The holes in the region of south 1,300 show two ore bodies, an upper and lower, separated in some holes by 400 to 600 feet of lean moderately altered rock like that over the west ore body. Still farther south, at the south 2,100 lines, the upper and lower ore bodies coalesce to give a thickness varying up to 1,500 feet and more. The lower portion of this ore body probably extends westward to join the western body previously described.

Still farther south this great mass of copper-bearing rock ends abruptly against the pyritic zone which swings around from the north as shown on Figure 1.

Across the strike of the western part of the ore body from north to south the supergene sulphide zone may be in the pyritic zone on the north end, in the chalcopyrite zone somewhat farther south, and in the lean hanging-wall rock still farther south. In this area the contact of the oxide zone with the secondary sulphide zone dips sharply southward as shown by Figures 4 and 5. This results in a rapid thickening of the oxide zone as the contact with the Gila (?) conglomerate dips more gently southward. In general, the oxide zone to the south lies in the lean hanging wall rock and thus is low grade, with more or less unoxidized sulphide in the impervious portions. The secondary sulphide zone is also poor under this rock, and evidence of enrichment disappears completely in some of the southernmost holes (Fig. 4).

The base of the Gila (?) conglomerate as determined by the San Manuel fault dips westward along the drill grid at about 30°. The secondary sulphide zone in sections parallel to the drill grid (N. 60° 10′ E.) is irregular, but approximately horizontal except in the southeastern part of the deposit. As a

result the fault transgresses the oxide zone nearly eliminating it, and also the secondary sulphide zone at west 1,800 and beyond in the region of south 100 to south 500. Farther south the zones are deeper and at places no supergene zone exists. Along the east side of the outcrop of the ore zone, the West fault

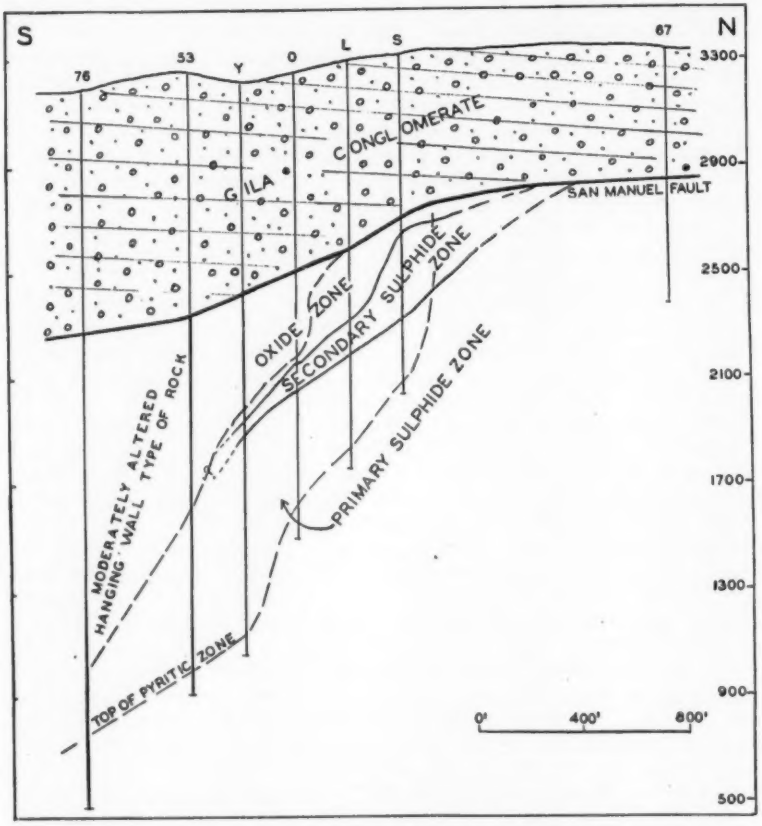


FIG. 4. Cross section of San Manuel Copper Deposit along W 1,400 of drill grid.

dips to the east about 70°. At depth the secondary sulphide zone has a thickness of 150 to 400 feet in this area and appears to end abruptly at greater depth. Only a few drill holes penetrate this area so the geology is incompletely known, but to the southeast lies the largest part of the ore body, apparently somewhat beyond the zone of faulting. The variation in depth of oxidation and of the

supergene sulphide formation in the eastern portion of the deposit presents a puzzling problem.

In the northern portion of the eastern area the top of the supergene sulphide zone lies at depths of 1,200 to 1,550 feet (altitude 1,500 to 1,700). The thickness ranges from 35 to 380 feet although two holes show no supergene sulphide zone worthy of the name. The grade of ore likewise shows wide variation. In part this is a result of differences in the character of the primary mineralization, both within the present supergene sulphide zone and the oxide zone, which must have yielded the copper added to the sulphide zone. In hole 72 drilled by the Magma Copper Company at the east end of the area, a zone 195 feet thick contains some chalcocite, but averages only 0.276 percent copper. In contrast the chalcocite zone in hole 44 is 140 feet thick and averages 2.081 percent.

Between south 900 and south 1,700. the top of the supergene sulphide zone rises abruptly to depths of 520 to 700 feet (elevations 2,500 to 2,300). Whether this is a continuous rise or an abrupt displacement as a result of faulting is not evident from drill holes spaced 400 feet apart. Faulting seemed a good possibility until it became apparent that the pyritic zone penetrated at greater depth did not show a corresponding displacement. Farther east, however, in the Houghton Group exploration (supervised by the Inspiration Copper Company) the Cholla fault definitely drops the east side 800 feet with a corresponding displacement in oxide, supergene sulphide, and hypogene sulphide zones.

If the fault explanation is thrown out, two possibilities remain. The first is an irregularity of 1,000 feet in the depth of oxidation. The walls of the open pit at Bingham or the Sacramento pit at Bisbee are sufficient evidence that oxidation and consequently enrichment vary considerably in depth. The second possibility is that tilting of the deposit since enrichment has resulted in a very different relation to the present surface from the relation to the land surface which existed during oxidation and enrichment. The northeast dip of the Gila (?) conglomerate over a wide area is evidence of tilting although some initial dip may have been present. North of the San Manuel area, the conglomerate dips to the northeast as much as 60° so that considerable tilting is indicated. This tilting alone does not account for the abrupt rise of the zone of enrichment, but, in view of the complex faulting in this and other regions of southern Arizona, it may well be that the rocks in this area have been tilted more than once. After considerable study and thought, the writer is inclined to the view that the present situation is a result of all three factors, that is, irregularity of the original depth of oxidation and enrichment, faulting and tilting. Of these tilting probably explains the most puzzling irregularities.

Primary Sulphide Mineralization.—The present shape of the primary sulphide zone is determined by the modification of the original ore body by oxidation and enrichment, and no doubt to some extent by post-mineral faulting. Throughout the explored area, the primary sulphide zone extends below the bottom of the deepest drill holes, but in most holes the lower part is highly pyritic and low in copper as noted above. The upper surface of the primary (hypogene) sulphide zone is normally in contact with the supergene sulphide

zone, but at places highly oxidized material rests directly on primary sulphide, generally pyrite. At the western end of the explored area the conglomerate rests directly on lean primary sulphide. The top of the primary sulphide zone grades from smooth to irregular in different parts of the area, but great variations in altitudes are common. This is shown by Figures 2–6. In hole E

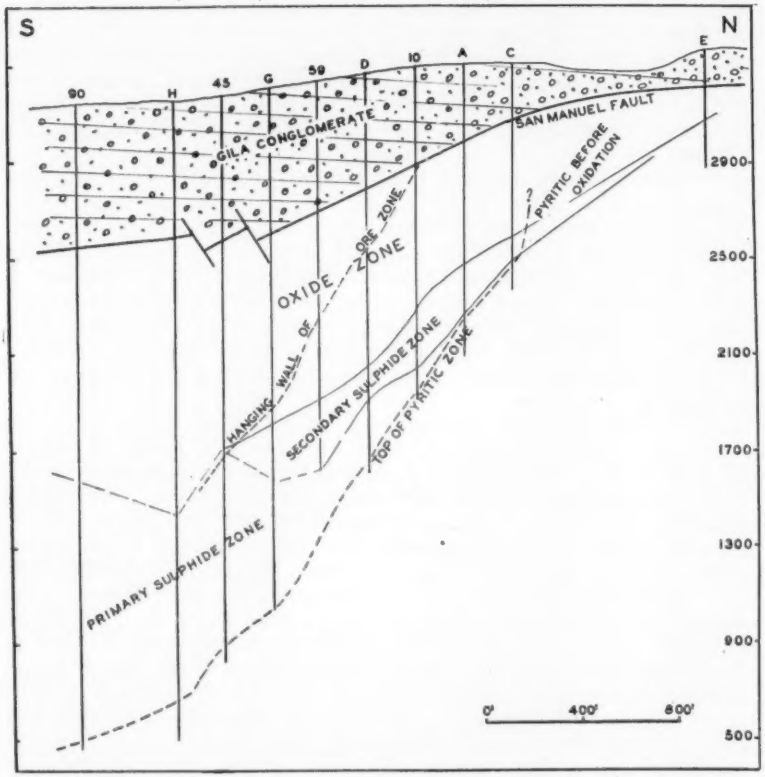


FIG. 5. Cross section of San Manuel Copper Deposit along W 600 of drill grid.

heavy pyritic material was cut at a depth of 285 feet, whereas in hole 79 predominant sulphide material was first struck at 1,630 feet. The oxide in several holes extended to depths varying from 1,200 to 1,500 feet. Possible reasons for such variations will be discussed after the description of the zones of oxidation and enrichment.

The character of the primary sulphide mineralization at San Manuel varies

according to location. In a previous report [10] four types of alteration were described. The first zone cropping out in a small roughly circular area is characterized by an intense alteration of porphyry to kaolinite and alunite believed to be largely a result of hydrothermal alteration. The outcrop of the altered rock is cut-off at the east side by the overlying conglomerate. The alteration probably extended northeastward, but lack of data prevents giving it any definite limits.

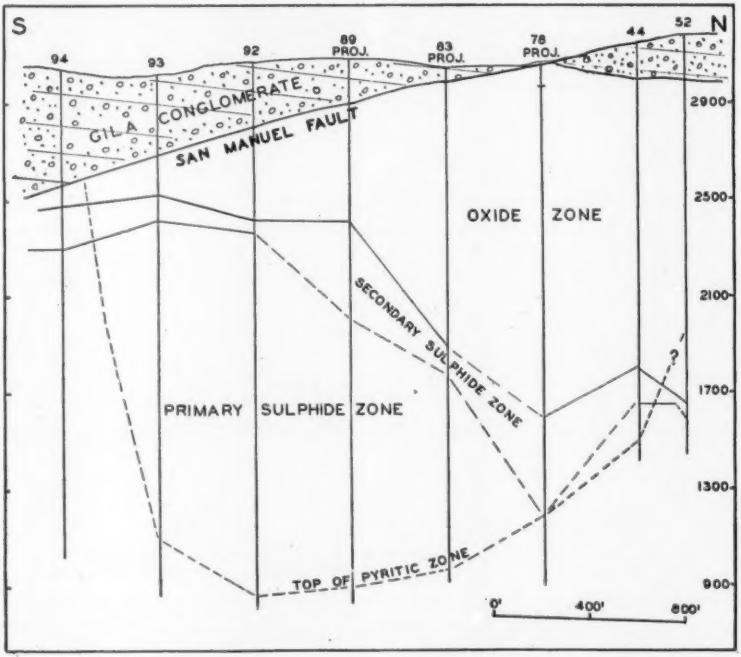


FIG. 6. Cross section of San Manuel Copper Deposit along E 2,000 of drill grid.

Surrounding the inner area is a zone characterized by a moderate red color at the surface and highly pyritic material at depth. Hydromuscovite is the characteristic alteration product in this area. This pyritic material almost invariably underlies the copper ore and has been penetrated by the lower part of scores of drill holes. The rock is intensely mineralized and carries much more sulphide than the copper zone. The amount of sulphide concentrate obtained from a single pan of sludge always increases greatly when this zone is penetrated and the copper content decreases. The bottom of most holes averages

[10] Schwartz, G. M., op. cit.

from 0.1 to 0.2 percent copper. Holes drilled well out into the pyritic zone show very little copper; even very heavy pyritic material assays less than 0.1 percent copper. In some of the more recent drill holes at the east end of the deposit, the pyritic alteration appears to have affected the rock above the chalcopyrite zone as well as below it. The details are still obscure. The polished concentrate from this zone consists of pyrite with a few grains of chalcopyrite and pyrite grains with inclusions of chalcopyrite (Fig. 11). A few grains of rutile occur in some concentrates and some contain magnetite or martite (Fig. 24).

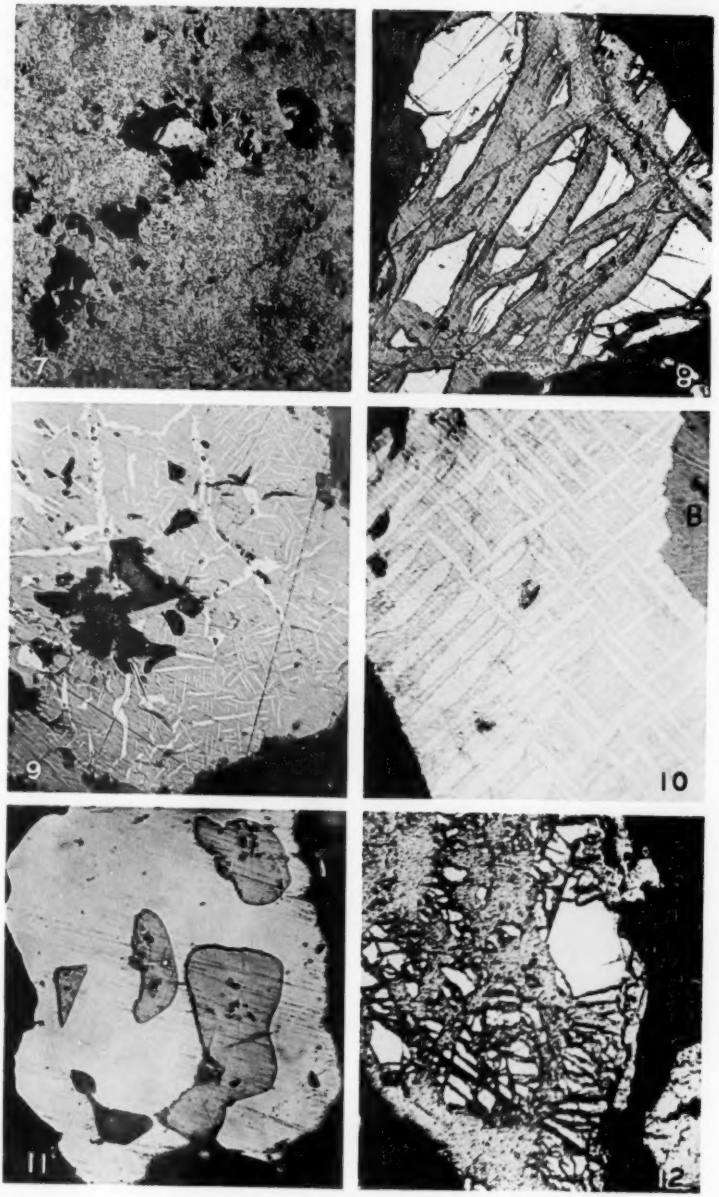
The primary copper mineralization as previously described formed a wide, rather steeply inclined tabular-shaped body overlying the pyritic material. At the southeast this simple relation does not hold, or is difficult to recognize because of the complicated fault and oxidation-enrichment patterns. This rock is impregnated with sericite but also contains chlorite, kaolinite, hydromuscovite, beidellite, leucoxene, and rutile.

The primary ore consists of disseminated sulphide in monzonite porphyry (Fig. 7) and quartz monzonite. Pyrite and chalcopyrite are abundant and vary greatly in relative amounts, but as a rule pyrite predominates. In the concentrates the two minerals have mostly broken apart but inclusions of chalcopyrite in pyrite (Fig. 11) are common and pyrite is occasionally observed to have been replaced by chalcopyrite (Fig. 8).

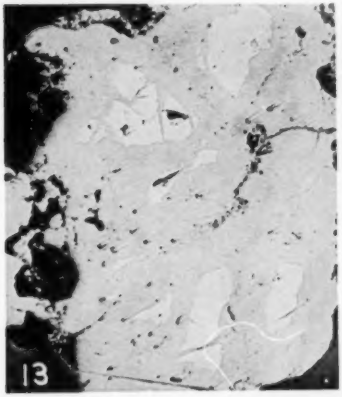
Rutile is a common but rarely an abundant mineral in the sulphide concentrates. Rutile has been observed in most thin sections and to a considerable extent exists in clusters within areas formerly occupied by biotite. It is a result of the freeing of titanium when the biotite was destroyed by hydrothermal alteration. Inclusions of chalcopyrite occur in rutile indicating essentially contemporaneous formations of the two minerals. Other than chalcopyrite the only copper mineral in the primary ore is bornite. The evidence seems good that small amounts of bornite are primary, although some of it is associated with supergene chalcocite and is secondary.

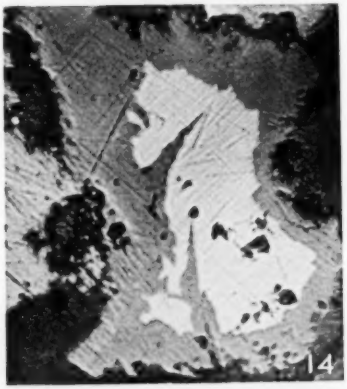
Bornite has been observed intergrown with chalcopyrite and both replaced by chalcocite (Fig. 18). This is interpreted as a primary intergrowth of chalcopyrite and bornite, possibly a replacement of chalcopyrite. Both are replaced by supergene chalcocite. In one specimen ex-solution textures of bornite with blades of chalcopyrite and stringers segregated along grain boundaries were observed (Fig. 9), also a possible eutectoid texture of large chalcopyrite spindles in a fine-grained intergrowth of bornite-chalcopyrite (Fig. 10).

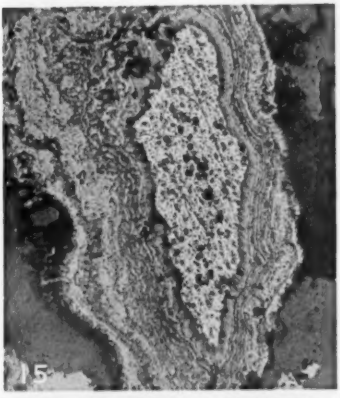
FIG. 7. Chalcopyrite (black) in sericitized porphyry. Hole 6, 1105′. × 50.
FIG. 8. Pyrite partly replaced by veinlets of chalcopyrite. Hole 14, 940′. × 120.
FIG. 9. Chalcopyrite in laths and stringers along grain boundaries of bornite. Ex-solution texture. Hole 10, 1225′. × 500.
FIG. 10. Chalcopyrite-bornite intergrowth and adjacent area of bornite. (B) Ex-solution texture. Hole 10, 1225′. × 500.
FIG. 11. Chalcopyrite inclusions in pyrite. Primary structure. Hole 13, 1050′. × 100.
FIG. 12. Pyrite remnants in chalcocite. Supergene replacement. Hole 14, 940′. × 150.

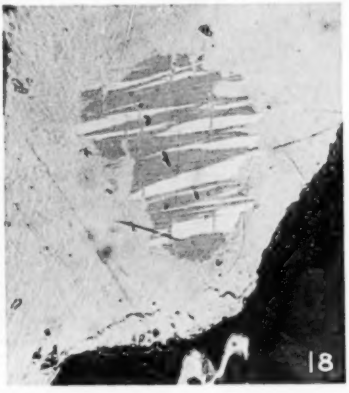


FIGS. 7-12









FIGS. 13-18

Similar textures have been shown experimentally to result from ex-solution.[11] Natural occurrence of these textures is unknown in copper ores and recent investigation indicates that these are a result of overheating in drying the concentrates.

The outer or marginal alteration affected the hanging-wall rocks of the main belt of mineralization. Generally the rock showing this type of alteration appears fairly fresh, but in thin section the groundmass is a complex of alteration products including secondary biotite, hydrobiotite, sericite, epidote, zoisite, chlorite and small amounts of several clay minerals. Plagioclase phenocrysts of the porphyry are considerably altered to sericite, chlorite and clay minerals. In the area of drilling this rock consistently carries small amounts of copper. Zero assays are so uncommon as to excite a special look at the rock cuttings for other unusual features. The persistence of small amounts of pyrite and chalcopyrite in moderately altered rock over large areas suggests the possibility of other ore bodies beyond those now known.

Oxidation.—Oxidation has been extensive but variable in the San Manuel deposit. The better grade oxide ore no doubt represents the oxidation of former supergene chalcocite ore. Many holes drilled through the hanging wall of the main copper ore zone have long columns of very lean oxide usually containing less than 0.3 percent copper because the primary mineralization was weak. Throughout the oxide zone chrysocolla is the predominant visible copper mineral.

The oxidized portion of the deposit varies greatly in thickness owing to several factors. The thickness of the conglomerate over the deposit ranges from a feather edge at the small outcrop area to 1,140 feet at the west end in hole 82. The Gila (?) conglomerate is 1,395 feet thick in hole 86, to the southwest of the deposit. Where a great thickness of conglomerate exists, the oxide zone has been largely cut-off by faulting as indicated on Figure 2. Tilting has probably been responsible for preservation of some of the very thick portions of the oxide zone.

During the early drilling, it was thought that there was a fairly close relation between the bottom of the zone of principal oxidation and the water table.

[11] Schwartz, G. M., Intergrowths of bornite and chalcopyrite: ECON. GEOL., vol. 26, pp. 186–201, 1931.

FIG. 13. Chalcopyrite remnants in chalcocite. Supergene replacement. Hole 6, 710′. × 200.

FIG. 14. Chalcopyrite remnant in bornite. Supergene replacement. Hole 6, 710′. × 400.

FIG. 15. Pyrite replaced by chalcocite with concentric structure. Hole 2, 715′. × 120.

FIG. 16. Chalcopyrite (Ch) replaced by bornite (Bn) which is replaced by covellite (Cv); bornite and covellite in turn replaced by chalcocite (Cc). Hole 7, 710′. × 550.

FIG. 17. Chalcopyrite remnant in covellite. Supergene replacement. Hole 7, 995′. × 300.

FIG. 18. Remnant of an intergrowth of chalcopyrite (white) and bornite (dark gray) in chalcocite. Bornite probably replaced chalcopyrite in the primary ore. Chalcocite is supergene. Hole 10, 995′. × 350.

This, however, proved to be merely a coincidence resulting from the location of the holes. As drilling extended out from the original locations, it became evident that the present water level has nothing whatever to do with the depth of oxidation. The bottom of the so-called zone of oxidation is usually not sharp, but rather a gradual decrease in oxides and an increase in sulphides. In some holes there is an alternation of zones of fairly complete oxidation with zones of little or no oxidation. In a general way, however, it is possible to designate an approximate depth at which the zone of extensive oxidation ends. This depth ranges from 285 feet (altitude 3,088) in hole E, which is on the southwest slope of Red Hill, to 1,630 feet (altitude 1,558) in hole 79. The former is several hundred feet above the present water table and the latter is nearly a thousand feet below it. Other holes show a fairly continuous gradation between the two extremes. Some of the holes that have a large thickness of the moderately altered hanging-wall type of rock have no oxide or secondary sulphide zone in the true sense, for example, holes 53 and 76 of Figure 4. This rock was fairly impervious and weathering solutions penetrated it only locally so that except locally, the small amount of sulphide present escaped oxidation. It is probably better not to try to designate zones of oxidation and enrichment under such conditions.

Extensive observations have been made of the water levels in the drill holes during drilling and at monthly intervals thereafter. The writer is particularly indebted to the San Manuel Copper Corporation for use of their data. In a general way the altitude of the static level in the holes ranges from about 2,950 at the west end of the drilled area to 2,480 at the east end which is nearer to the San Pedro River. The altitude of the river at Mammoth is 2,330. The static level is somewhat erratic from hole to hole, and there are also some surprising variations from month to month. T. S. Lovering [12] reported that several of the abnormally high water levels being measured in checkholes proved to be just above cave-ins when he attempted to measure temperatures in March 1948. The data suggest that the rock has low permeability, except in local zones, as would be expected in intrusive igneous rocks cut by faults.

Recent pumping from several of the holes indicates a rather free flow of water into those holes with very slow depression of the water level on continuous pumping.

[12] Personal communications.

FIG. 19. Pyrite in goethite with concentric structure. Oxidized zone. Hole 9, 625′. × 120.

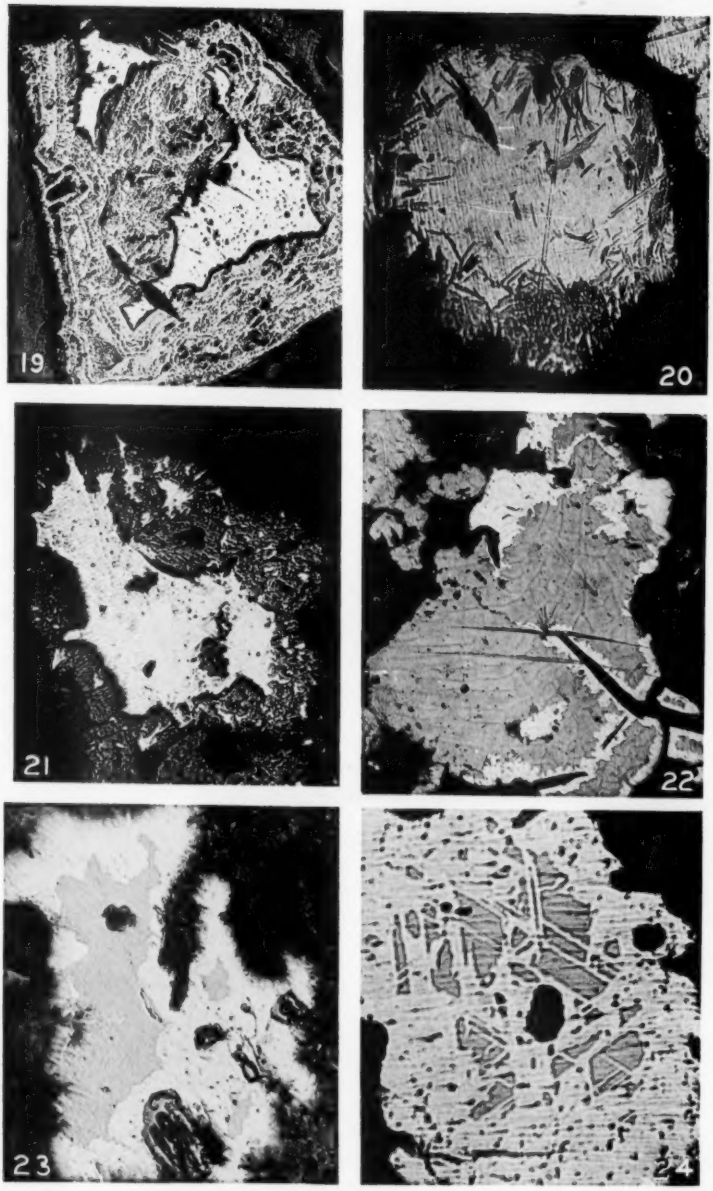
FIG. 20. Chalcocite partly replaced by covellite (dark gray); common in supergene sulphide zone. Hole 6, 825′. × 530.

FIG. 21. Chalcocite (white) partially replaced by cuprite. Chalcocite probably supergene. Hole 10, 1015′. × 275.

FIG. 22. Native copper (white) replaces chalcocite rim and along blade-like gangue. Hole 13, 1050′. × 100.

FIG. 23. Remnants of chalcocite (gray) in native copper (white); cuprite (c) indents native copper. Hole P, 1550′. × 350.

FIG. 24. Magnetite remnants in hematite (martite) grain. Possibly hydrothermal oxidation. Hole T, 605′. × 340.



FIGS. 19-24

At the outcrop, chrysocolla is the prominent copper mineral of the oxidized zone, and this is true throughout insofar as the churn drill cuttings permit one to judge. Locally malachite and rarely azurite occur, but these minerals seem to account for little of the copper values. Because of the abundance of red iron oxide in the ore, it is difficult to estimate the amount of cuprite. At the bottom of the oxidized zone, where supergene chalcocite has been subjected locally to oxidation, cuprite is fairly common and was identified without difficulty (Fig. 21). According to available data, however, cuprite is not abundant at San Manuel. Panning of sludge from the oxide zone rarely shows much cuprite. It seems probable that the availability of silica prevented much cuprite from forming. Cuprite seems to have formed when the zone of oxidation moved down into previously formed chalcocite, but chrysocolla seems to have replaced both cuprite and chalcocite. This is a normal process but is of more than usual importance in a deposit with a complicated history and apparently a variable relation to the water table. Cuprite often forms rims or zones around grains of chalcocite; also a network of minute veinlets of cuprite throughout the chalcocite was frequently observed.

It was noted that in many holes there does not appear to be enough chrysocolla to account for all of the copper content. It is possible that the copper is partly in cuprite mixed with and masked by the prevalent iron oxide. The writer has observed that in the Bisbee deposits rich oxidized copper ore at places appears to be merely a mass of iron oxides.

Hundreds of polished concentrates containing iron oxide have been examined under the microscope. The greater part of the iron oxide resulted from the oxidation of pyrite, some doubtless came from chalcopyrite, and a small amount resulted from the oxidation of magnetite (Fig. 24). Remnants of pyrite are abundant in some samples. The characteristic feature of the iron oxide is its red color which is prominently shown on Red Hill. At depth the external red color is usually not conspicuous, but examination of the polished iron oxide grains under polarized light reveals that most of them are a bright- to dark-red color. Nevertheless, the grains show the concentric structure (Fig. 19) usually found in goethite. Grains of this red oxide carefully picked out and heated in a closed tube give off abundant water. Professor John W. Gruner has kindly made X-ray patterns of powdered material, and these show the presence of both goethite and hematite. It is concluded that red iron oxide of this type consists mainly of goethite which is colored red by finely divided ferric oxide. As far as the writer can determine, pure goethite never shows a red color either in powder or in polarized light on polished surface. The anisotropism of the red oxide aggregate from San Manuel is more characteristic of goethite than of hematite, and in spite of its red color the aggregate consists mainly of goethite.

Supergene Enrichment.—The downward enrichment of copper in the San Manuel deposit has been extremely variable. Considered as a whole, the amount of enrichment is not great. The Magma Copper Company in its annual report for 1946 states that there are 66,000,000 tons of oxide ore averaging 0.7 percent copper. This quantity of oxide ore is a good indication that conditions did not favor much solution of copper in the oxide zone and redepo-

sition of it below the water table. This is not the case in the eastern part of the ore body where leaching was extensive and there is very little oxide ore. The situation is, however, very misleading when applied to individual drill holes. Some holes have no recognizable zone of supergene enrichment, but the oxide and primary sulphide zones are in contact. In general these holes are located so that a great thickness of slightly mineralized hanging-wall rock overlies the sulphide (Fig. 4). In many places these rocks were probably too impervious to permit much downward percolation.

Some drill holes, for example holes U, 15, 16, and 76, have a supergene sulphide zone, but with such a small amount of chalcocite there has been little enrichment. Many drill holes along the western portion of the ore body show a moderate enrichment by chalcocite, but the average grade is only a few tenths percent above that of the primary chalcopyrite-pyrite ore. A detailed study of holes 4, 6, 7, and 10 showed a total of 775 feet of drilling in the supergene sulphide zone that averaged 1.03 percent copper. The corresponding primary sulphide zone showed an average of 0.522 percent copper for a total of 500 feet of drilling. This is lower grade than average primary ore as many holes show large footages that average 0.8 percent. Because, as a rule, enrichment is not great, the supergene sulphide zone has been outlined on the basis of presence of supergene chalcocite rather than on the amount of enrichment in copper content.

Holes showing pronounced enrichment are mainly in the eastern part of the deposit, but the supergene sulphide zone is generally thin in this area. For example, hole 92 near the south edge has 275 feet of conglomerate above 390 feet of oxide zone averaging only 0.1 percent copper. This is believed to have been originally high in pyrite but low in copper. The supergene sulphide zone is 40 feet thick and averages 1.793 percent copper. The primary zone below averages 0.877 percent. Hole 15 drilled by the Bureau of Mines [13] furnishes a good example of an enriched zone in lean rock that happened to lie just above better grade primary sulphide ore. The following tabulation gives the esssential facts.

0–365	Gila (?) Conglomerate.
365–1,300	Oxide zone, weak mineralization, sulphides locally. Average copper at 490–1,300 feet, 0.328 percent.
1,300–1,380	Partially oxidized supergene sulphide. Zone of fair mineralization. Average copper 0.545 percent.
1,380–1,415	Principal zone of supergene enrichment. Average copper 0.792 percent.
1,415–1,475	Zone of weak enrichment as shown by microscopic examination of concentrates. Average copper 0.858 percent.
1,475–1,945	Primary sulphide zone with good chalcopyrite. Average copper 0.90 percent.
1,945–1,990	Primary sulphide zone with high pyrite. Average copper 0.432 percent.

[13] Chapman, T. L., op. cit., p. 65.

The interpretation of the extreme variability of supergene enrichment depends on a very careful correlation of the assay data, including oxide-sulphide ratio, with the mineralogic data obtained by detailed microscopic studies and with the kind of alteration or primary mineralization. The nature of the supergene sulphide zone is very different in the pyritic zone, the chalcopyrite zone and the lean hanging-wall zone. In a series of holes, variations in grade of the supergene sulphide zone are readily explained by the differences in the primary mineralization. In the pyritic zone, a good precipitant of chalcocite was available and the amount of chalcocite depended on the copper available from above because there was little in the primary pyrite. In the chalcopyrite zone, a fair amount of copper was originally present and chalcopyrite was a good precipitant along with pyrite. Moderate enrichment thus resulted in good ore. In the hanging-wall zone, mineralization was weak, and the rock was comparatively tight. Thus there was not much copper available, solutions had trouble getting through from above, and there was a lack of chalcopyrite and pyrite to act as precipitants. Under these conditions supergene sulphide zones will contain little copper.

The greater part of the copper in the supergene sulphide zone is in chalcocite so the paragenesis of chalcocite has much significance. Most of the chalcocite replaces either pyrite or chalcopyrite. Where chalcopyrite is fairly abundant, as in the chalcopyrite-sericite mineralized rocks of the main ore zone, chalcocite selectively replaces chalcopyrite. The evidences of this are the numerous remnants of chalcopyrite in the chalcocite grains (Fig. 13), and the comparative scarcity of pyrite remnants even though pyrite is common in the ore. In contrast, where chalcopyrite is scarce or absent in the supergene ore, remnants of pyrite (Fig. 12) often occur in great abundance. Commonly chalcocite which has replaced pyrite shows a concentric structure (Fig. 15), that has been previously described as a feature of the Globe ore.[14] Also in a massive appearing chalcocite veinlet from the deposits at Ray, Arizona, the writer has recently found similar structures, some with grains of pyrite remaining but many with pyrite entirely replaced.

Etching the chalcocite with weak HNO_3 reveals a very fine etch pattern of minute grains. Tolman[15] has referred to this as metacolloid texture. Whether or not the colloidal state has entered into its formation is a question, but Tolman's description fits the chalcocite at San Manuel precisely.

Covellite is not an abundant mineral at San Manuel, but it is common in the supergene zone (Fig. 20). It is unknown as a primary mineral. Because covellite is not abundant, it is not possible to state its relations as definitely as those of chalcocite; moreover it seems to have a somewhat more varied occurrence. It has not been observed replacing pyrite, but in a small way it does replace chalcopyrite directly (Fig. 17), and rarely replaces bornite (Fig. 16), a very minor constituent of the ore. The most common occurrence of covellite is as small blades and feathery aggregates in chalcocite (Fig. 20). In some grains the covellite is so evenly distributed that an origin by ex-solution is sug-

[14] Schwartz, G. M., Notes on the textures and relationships in the Globe copper ores: ECON. GEOL., vol. 16, pp. 322–329, 1921.

[15] Tolman, C. F., Observations on certain types of chalcocite and their characteristic etch patterns: Am. Inst. Min. Eng. Trans. vol. 54, pp. 402–435, 1916.

gested as shown by Bateman and Lasky [16] for the Kennecott ore. In other ocurrences the covellite penetrates the chalcocite grains around the border and seems to replace them. Rarely chalcocite replaces covellite (Fig. 16).

Bornite is a sparse mineral in the San Manuel ore although minute amounts may be observed on many polished surfaces. Very small amounts show crystallographic intergrowths with chalcopyrite, suggesting a contemporaneous hypogene origin (Fig. 18). Other small amounts penetrate chalcopyrite extensively and are probably hypogene replacements. A very narrow, faint band or halo of bornite around a remnant of chalcopyrite in chalcocite of supergene origin is a more common occurrence. At places the bornite develops more extensively as a replacement of chalcopyrite (Fig. 14), and may be replaced in turn by other copper sulphides (Fig. 16). Centripetal replacement of pyrite by chalcopyrite, bornite and chalcocite is indicated in some grains studied, and in the writer's experience this is always supergene.

In summary it may be said that there is a very small amount of hypogene bornite contemporaneous with chalcopyrite; likewise, a small amount that is hypogene but later than chalcopyrite and a small but widespread amount that is a supergene replacement of chalcopyrite.

From a practical viewpoint bornite is of little importance in the ore because of the small amount present. Its occurrence as a supergene mineral is due to a local or transitory excess of iron that caused bornite to form instead of chalcocite. At most places the copper-bearing solutions appear to have soon replaced the bornite, leaving only a thin band as evidence of its passing.

Native Copper.—One of the most perplexing mineralogical problems at San Manuel is the explanation of the occurrence of native copper. This mineral is present in small amounts in many drill holes where the supergene sulphide zone is penetrated. As a rule it occurs in the lower portion of the supergene zone, although absent in the upper and richer portion. Only one hole was noted where native copper was abundant at the top of the supergene sulphide zone. In hole number 89 a heavy concentrate of native copper was obtained by panning the sludge from 680 to 690 feet with lesser amounts in chalcocite below. This occurrence is a normal example of abundant oxygen robbing chalcocite of its sulphur leaving native copper, and the copper is partly oxidized to cuprite. It is certain that part of the native copper lower down in the chalcocite zone forms by replacement of chalcocite (Figs. 22 and 23). Hole 1 furnishes a good example of the occurrence of native copper. This hole started in the ore outcrop and passed through 520 feet of highly oxidized material averaging 0.614 percent copper. The supergene sulphide zone extended from 520 to 740 feet and averaged 1.158 percent copper. The hypogene (primary) zone carried fair copper values from 740 to 790 feet, but below 790 feet graded into the pyritic footwall rock that averaged 0.291 percent copper from 790 to 990 feet. At about 680 feet, that is, in the lower portion of the chalcocite zone, native copper appears in considerable amounts. This formed in part, if not completely, from chalcocite which is rimmed and veined by native copper. Chalcocite also occurs as remnants in some of the large fragments of native copper. It should

[16] Bateman, A. M., and Lasky, S. G., Covellite-chalcocite solid solution and ex-solutions: ECON. GEOL. vol. 27, pp. 52–86, 1932.

be noted that there are 160 feet of supergene sulphide above the point where the native copper appeared and that the native copper occurs throughout a thickness of 60 feet.

Thirty-two other holes which illustrate similar conditions are shown on Figure 1. Although there is good evidence of the formation of some native copper from chalcocite, there is much copper which shows no remnants of chalcocite. Therefore the possibility exists that some native copper was precipitated directly from supergene copper-bearing solutions.

The formation of native copper from chalcocite must be a result of an oxidation of the sulphur of the chalcocite, possibly by ferric sulphate. The main difficulty is in explaining how the ferric sulphate passed through the upper part of the chalcocite zone without reducing the chalcocite. If the occurrence were simply a sporadic affair in one or two holes, it might be accounted for by a lateral access of solutions, but the prevalence indicates a chemical condition in the lower part of the chalcocite zone favoring reduction of chalcocite on a widespread but usually small scale. The presence of native copper far down in the sulphide ore may well be connected with the abundant goethite found in both the supergene and hypogene copper sulphide zones. Both suggest the presence of oxygen at depth, but as will be shown the two do not occur together to any great extent.

Occurrence of Iron Oxide Below the Oxide Zone.—Iron oxide is abundant in the oxide zone as would be expected of a pyritic deposit. An unusual feature is the persistence of iron oxide (red goethite) in the chalcocite ore and also below important secondary sulphide. Study of assays of oxide copper [17] and of the mineralogy shows that in many holes goethite, which has formed by oxidation of pyrite, continues well below the place where copper suffered appreciable oxidation. This is true in holes A, H, V, 3, 6, 10, 44, 56, 79 and perhaps others.

[17] The assay data available are of importance in the interpretation of the geology. For each 5 foot section of all drill holes a total copper assay is available made under a standard procedure (Morenci Method) for low-grade copper ore. In addition a determination of oxide copper is made for all samples that assay an appreciable amount of total copper.

The procedure for determination of oxide copper as supplied by San Manuel Copper Corporation is as follows:

Procedure for Determination of Oxide Copper

1. Weigh 5 gms pulp into small vial (size 1" × 3–¾", with screw cover. Approx. capacity = 45 cc).
2. Add 30 cc saturated solution SO_2 (60 cc H_2SO_4 + 2500 cc H_2O, saturated with SO_2).
3. Cap bottles and agitate on shaker table 1 hour.
4. Remove and filter.
5. Wash 3 times with dilute H_2SO_4 (hot).
6. Wash 3 times with water (hot).
7. Add 5 cc H_2SO_4 to filtrate, bring to boil. While boiling add 15 cc of 20% solution $Na_2S_2O_3$. Boil until solution is clear, or copper is precipitated.
8. Filter and wash 3 times with H_2O.
9. Ignite.
10. Transfer ignition precipitates to 250 cc beaker, add 10 cc H_2O and 5 cc HNO_3. Boil until all Cu is in solution (about 5 minutes).
11. Cool and neutralize with NH_4OH, and 10 cc acetic acid and boil.
12. Cool and titrate.

This procedure would seem to exclude native copper from the oxide determination. If the sulphide copper is obtained by difference between total copper and oxide copper assays, the sulphide copper would be high in samples containing native copper.

It is especially difficult to account for so much oxidation of pyrite below chalcocite which oxidizes and dissolves more readily than pyrite.[18] Perhaps the explanation lies in the structural changes in the region. The evidence seems conclusive that the region was tilted to the northeast about 30° after the deposition of the Gila (?) conglomerate in Pliocene and Pleistocene time but before the deposition of the alluvial slope deposits of the San Pedro Valley which lie unconformably on the conglomerate. Furthermore, vertical sections of the deposit (Figs. 4–5) show a pronounced dip of the supergene sulphide zone to the south. The oxidation and enrichment evidently took place before the deposition of the conglomerate, so it is difficult in the present stage of knowledge of the deposit to visualize the structural attitude of the ore body when enrichment took place. It is possible, even probable, that part of the deep oxidation took place at a different time and under different structural and climatic conditions from those during supergene enrichment. It is also possible that some other unusual chemical condition resulted in an access of oxygen or an oxidizing agent to the sulphide at depth. In studying the polished sections the possibility of an oxidation later than chalcocitization was considered, but the lack of oxidation of chalcocite to cuprite in most holes, except at the very top of the supergene sulphide zone, seems to eliminate this as an explanation of the deep goethite lying beneath unoxidized chalcocite. It should be emphasized that much oxidation of chalcocite undoubtedly took place as erosion and oxidation migrated downward, but this has no obvious connection with the occurrence of goethite at depth. Perhaps oxidation of pyrite to goethite took place earlier than chalcocitization, although there is no direct evidence of this being the case.

GEOLOGIC HISTORY OF THE DEPOSIT.

The geologic history of the San Manuel deposit as revealed by rocks exposed in the area begins in Precambrian time with the intrusion of the quartz monzonite (Oracle granite). Paleozoic rocks are unknown in the vicinity of the deposit, but Paleozoic sedimentary rocks occur in Camp Grant Wash, 10 miles north of Tiger.[19] The quartz monzonite is intruded by a monzonite porphyry of fairly fine grain. This resembles some of the porphyries of other Arizona districts. At Ray, Miami and Globe,[20] 25 to 50 miles to the north, the porphyries are believed to be of Tertiary age, but even there the evidence is not conclusive, so little can be said regarding the monzonite porphyry at San Manuel except that it is presumably of the same age.

The porphyry was in turn cut by a series of small diabase dikes. Again there is an analogy with the Ray, Miami and Globe districts to the north.

Hydrothermal alteration and mineralization followed the intrusion of the diabase, but preceded the deposition of Gila (?) conglomerate during late Pliocene and Pleistocene time. Following mineralization there was a period of

[18] Emmons, W. H., The enrichment of ore deposits: U. S. Geol. Survey Bull. 625, p. 130, 1917.

[19] Peterson, Nels P., op. cit., p. 10.

[20] Ransome, F. L., The copper deposits of Ray and Miami, Arizona: U. S. Geol. Survey Prof. Paper 115, p. 123 and p. 59, 1919.

erosion sufficient to expose the porphyry and other mineralized rocks. During this period of erosion deep oxidation and supergene enrichment took place.

Whether there was extensive faulting preceding the deposition of the conglomerate is a question. Between some drill holes there appears to be a pronounced displacement of the supergene sulphide zone without a similar displacement of the base of the conglomerate. For this reason the possibility of faulting before the deposition of the conglomerate must be admitted.

Following the long period of erosion the Gila (?) conglomerate was laid down under conditions of pronounced relief and rapid erosion. The Gila (?) conglomerate is probably of late Pliocene and early Pleistocene age. Its deposition must have been followed by a period of tilting and faulting and intrusion of the felsite also followed deposition of the conglomerate. Presumably in late Pleistocene time the San Pedro Valley was developed with its pediments and alluvial slope deposits which lie with pronounced angular unconformity on the conglomerate. Faulting continued until late in the Pleistocene, as alluvial slope deposits occur faulted against the conglomerate. Renewed erosion has cut the present washes in the alluvial slope and down into the older rocks.

COMPARISON WITH OTHER DEPOSITS.

Study of the literature as well as visits to other disseminated copper deposits furnish evidence of similarities and contrasts.

Ajo.—The work of Gilluly [21] has shown that the deposit at Ajo was eroded, a blanket of oxidized ore and one of secondarily enriched ore were formed, and then the deposit was covered by a fanglomerate. After the deposition of the fanglomerate, the area was tilted about 50° southward, and another cycle of erosion followed, accompanied by oxidation but not by enrichment. This concept of tilting for which there is clear evidence at Ajo is helpful in interpreting the geology at San Manuel, particularly the low dip of the San Manuel normal fault. Tilting at San Manuel is indicated by the dip of the Gila conglomerate which averages 35° NE. The San Manuel fault probably had an original dip of 65° but was flattened to about 30° by this tilting. The tilting at San Manuel must have affected the attitude of the mineral deposit, but present data are insufficient to work out the details.

Ray and Miami.—The nearest large disseminated copper deposits to San Manuel are those at Ray about 25 miles north and at Miami 47 miles to the north. Ransome's [22] excellent description of these deposits furnishes several comparisons.

As at San Manuel, the supergene deposits at Ray and Miami are not related to the present topography. At Ray and Miami enrichment took place previous to the out-pouring of the dacite and the deposition of the conglomerate. Likewise, the oxidation and enrichment at San Manuel preceded the deposition of the conglomerate. The present maximum thickness of overburden is great in both areas.

[21] Gilluly, James, The Ajo mining district, Arizona: U. S. Geol. Survey Prof. Paper 209, 1946.

[22] Ransome, F. L., op. cit.

Ransome noted no recognizable control of the mineralization except minute fracturing. In the present state of knowledge this is emphatically true at San Manuel. Great irregularity in thickness of the supergene sulphide zones is characteristic. No evidence was obtained that the water table determined the lower limit of oxidation, but rather the exhaustion of oxygen was the important factor. Oxidation was deeper along favorable channels; as the channels are rarely vertical, oxidized material beneath protore or enriched sulphide is not surprising.

Ransome thinks slow enrichment results when chalcocite, chrysocolla, and malachite are eroded. This would explain the low ratio of enrichment revealed in many drill holes at San Manuel.

The selective replacement of chalcopyrite seems common in the deposits of both areas.

In comparison with the Utah copper deposit at Bingham, Utah, the San Manuel deposit seems much more pyritic, has even less primary bornite, and covellite is not as abundant in the supergene sulphide. Qualitatively, most of the textures and relationships of the ore minerals at one place may be duplicated at the other.

METHODS OF STUDY.

It is felt that the methods used on this project have been unusually fruitful and deserve description. Some of the details have been described in an earlier paper.[23]

Churn drilling was used for all but one hole, and each hole was sampled at five foot intervals. In addition to the usual samples for assay, a portion of the reject was caught and the slimes washed out to leave the coarser material that is referred to as a character sample. This was used for classifying the rock and describing the rock alteration and mineralization. In addition a portion of reject was caught and panned to eliminate all except the heavy minerals. Pan samples from the oxidized zone and the lean hanging-wall rock yielded too little concentrate to warrant saving. Samples of more heavily mineralized rock, even though oxidized, often yielded a concentrate, particularly of iron oxide. In samples from the sulphide zones abundant metallic minerals were common. The concentrates were then studied with a hand lens and when necessary with a binocular microscope. From the large number of concentrates from each hole, a sufficient number to characterize the material were selected for mounting in bakelite, polishing, and microscopic study. For this purpose a small mold giving a briquet of about ⅞ inch diameter is economical of both time and material. These briquets were then polished by rapid methods.[24] Bakelite XM9131 was found very good, but the ordinary black bakelite has been used also with excellent results. Several briquets were ground at the same time on a lead lap with 600 alundum and then given a brief rubbing on a ground glass plate also with 600 alundum to insure a perfect plane surface. Polishing was done on cloth laps successively with 600 alundum,

[23] Steele and Rubly, op. cit.

[24] See Short, M. N., Microscopic determination of the ore minerals: U. S. Geol. Survey Bull. 914, p. 42, 1940, for the general method.

chromic oxide and black magnetic rouge. For mounts with soft minerals a brief buffing with the magnetic oxide on billard felt is desirable. When done with groups of twenty or more samples, this method is very rapid and gives polished surfaces satisfactory for most purposes. With a little extra care surfaces suitable for photography at usual magnifications are easily obtained (Figs. 7–24).

CONCLUSIONS.

In the present state of knowledge, most conclusions concerning the San Manuel deposit must be considered tentative. Enumeration of them will nevertheless be helpful in furnishing definite statements to either verify or disprove by future work.

1. There is no determinable relation of the zone of supergene enrichment to the present surface or water table. The gradual fading out of the oxide zone in most drill holes indicates that the water table was not an important factor in enrichment.

2. The enrichment occurred before the deposition of the Gila (?) conglomerate. Faulting makes it impossible at present to relate the zone of enrichment to the surface on which the conglomerate was deposited.

3. Faulting and tilting have changed the attitude and position of the zone of enrichment, but details of the changes are not understood.

4. The great depth at which oxidized minerals are found in some holes (1,500 feet) is probably explained by deformation following oxidation and by burial beneath conglomerate. It is fairly certain that the depth of oxidation was great in any event.

5. The large amount of copper remaining in the oxide zone has several explanations. a. Abundant silica available in the ground waters to fix the copper in relatively insoluble chrysocolla. b. Arid climate suggested not only by the present climate, but by the persistence of red iron oxide throughout the oxidized material. c. Lean, rather tight, weakly altered hanging-wall rock with very low pyrite content.

6. The weak enrichment shown in many holes is also explained by the factors noted under 5. It is clear that a long column of oxidized ore of average grade is rarely underlain by a good supergene chalcocite zone, but there are a very few exceptions.

7. During supergene enrichment chalcocite selectively replaced chalcopyrite, but freely attacked pyrite if chalcopyrite was not present originally or had all been replaced.

8. Native copper in the zone of supergene enrichment, especially in the lower portion, is unusually persistent. It results, so far as present evidence indicates, from replacement of chalcocite presumably as a result of oxidation of the sulphur of chalcocite.

9. Bornite of both hypogene and supergene origin is present in very small amounts. Covellite as a supergene mineral also occurs in very small amounts.

UNIVERSITY OF MINNESOTA,
MINNEAPOLIS, MINN.,
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A SUGGESTED ORIGIN FOR THE SHELBY COUNTY, ALABAMA, LIMONITE ORES.

RHESA M. ALLEN, JR.

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ABSTRACT.

The limonite ores of Shelby, Alabama, which have been mined intermittently since 1846, occur as small grains and pebbles overlying a white sandy-clay zone, and as large masses or "dornicks" underlying the clay zone; all of which constitutes a blanket between the underlying Newala limestone of lower Ordovician age and overlying thrust mass of Talladega phyllite and slate of probable Precambrian age. The Talladega contains an abundance of small quartz veins, many of which carry pyrite. The Newala limestone locally is an extremely massive, fine-grained or "vaughanitic" high-calcium limestone, without conspicuous jointing or other fractures. Overthrusting of the Talladega locally on the dense Newala and regional uplifts in the Mesozoic and Cenozoic provided the setting for the leaching of the iron from the pyritiferous Talladega and its deposition and retention as limonite on the underlying, impervious Newala limestone.

INTRODUCTION.

THIS paper considers only the manner of occurrence and genesis of the limonite ores at Shelby and suggests a possible guide for future prospecting. Renewed activity of the Shelby mine and the increased demand for iron ore prompted study of this deposit in the hope that an understanding of its origin might encourage more extensive development in other areas where limonitic ores are known to occur. The genetic study does not consider the chemical factors involved in solution and redeposition of the iron.

The limonitic deposits lie just outside Shelby in Shelby County, Alabama, about 25 miles south-southeast of Birmingham and embrace an area of about 200 acres (Fig. 1). The area is served by the Louisville and Nashville Rail-

FIG. 1. Index map showing location of Shelby area.

road which at the present time is carrying ore to furnaces at Birmingham. Shelby is connected with Columbiana, and with Calera.

The history of mining development, an outline of the general geology, and several ore analyses have been given by Butts.[1] At the present time the limonite is being worked by the Shelby Sand and Ore Company.

GEOLOGIC SETTING.

The limonite deposits are localized along a thrust fault that has placed Talladega slates and phyllites (Precambrian?) above Newala limestone (lower

[1] Butts, Charles, Iron ore in the Montevallo-Columbiana region, Alabama: U. S. Geol. Survey Bull. 470, pp. 215–220, 1911. Also U. S. Geol. Survey Montevallo-Columbiana Folio, No. 226, 1940.

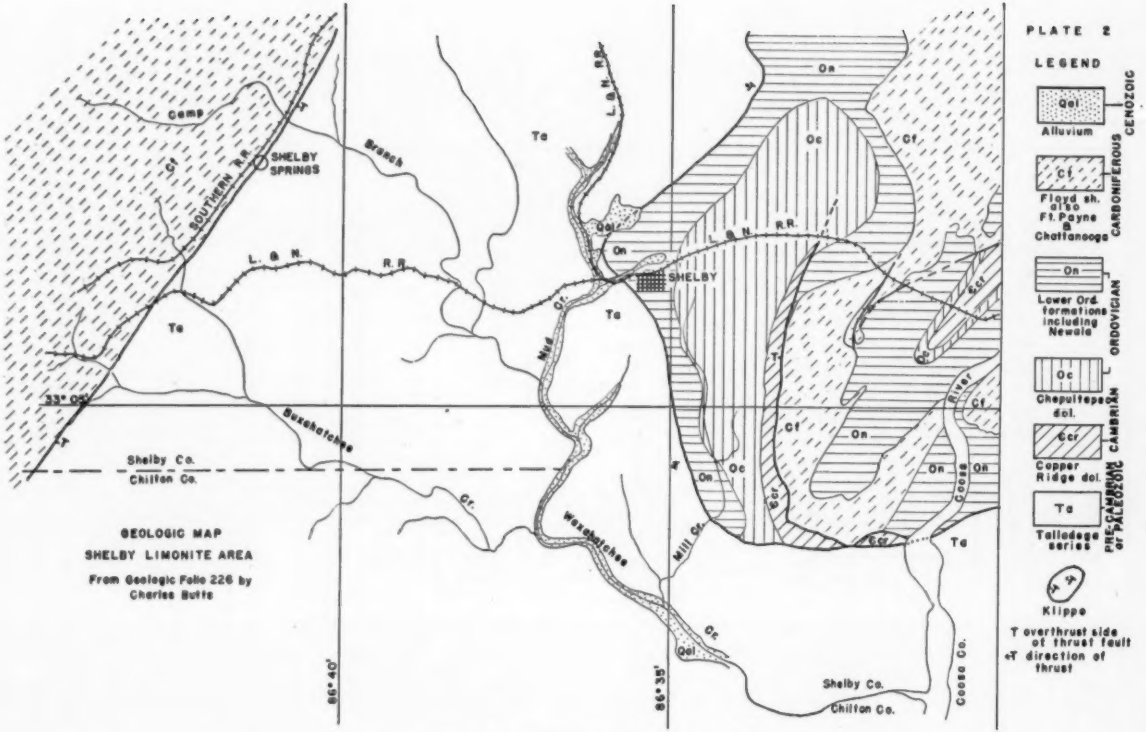

FIG. 2. Scale is approximately 2 miles to 1 inch.

Ordovician). Locally erosion has removed a part of the overthrust mass and has just exposed the underlying Newala limestone on which the bulk of the ore occurs.

Talladega Series.—The Talladega consists locally of grayish, greenish, and pinkish slates with subordinate phyllite, which weather to deep pink and yellowish gray. Significantly the series contains numerous small veins of milky quartz from a fraction of an inch to 5 inches thick which lie along the foliation and cleavage planes of the slates and phyllites. Most of these veins contain pyrite and some contain pyrite in abundance. Such pyritic veins are also contained in the Talladega near Heflin in Cleburne County and in several parts of Coosa County (both in Alabama), as well as in Polk and Haralson Counties, Georgia. Those in Georgia may be seen to advantage along U. S. Highway 27, south of the Central of Georgia overpass.

At Shelby the Talladega has been highly folded and locally has been sheared and changed to quartz-sericite schist. Because of the rather intense deformation the quartz has a "stretched out" appearance. The top and bottom of the series are not exposed and the thickness is not known. The age is regarded by Crickmay [2] as Precambrian.

Newala Limestone.—The Newala limestone, which takes its name from Newala, a post office on the Southern Railway between Calera and Montevallo, is generally undifferentiated from the Odenville limestone which overlies it but the two are readily distinguished. The Newala is generally a dark gray, fine-grained, compact, high calcium limestone whereas the overlying Odenville is argillaceous and cherty. In the immediate vicinity of Shelby the Newala is bluish-gray to dove colored, and in places is so fine grained and dense as to appear amorphous. It breaks with a splintery or conchoidal fracture like a typical vaughanitic limestone. The amorphous facies is nonpersistent laterally, but may repeat itself in a vertical section of several hundred feet, with intervening strata of dolomite or cherty and argillaceous limestone. The Newala is thin bedded and is singularly free of joints or other fractures. Lenses of thin bedded dolomite are relatively common in the upper part of the Newala and pinnacles of thin-bedded dolomitic limestone are exposed in an old working about a mile north of Shelby. Significantly the limonitic ore is scarce to nonexistent over the dolomite and impure limestone and is confined almost entirely to the areas of vaughanitic rock. The Newala contains a Beekmantown fauna and therefore is Lower Ordovician.

Structure.—The major geologic features of the Shelby area, as recorded in the Columbiana quadrangle mapped by Butts, are shown in Fig. 2. The map discloses that Shelby is located on the Newala just to the east of the trace of a major fault which forms the east margin of a klippe of Talladega. The west margin of the Talladega is marked by the same fault which passes through Shelby Springs. The dip of the fault in the Shelby area, as revealed in some of the old pits, averages 15 degrees west, with many local flattenings and steepenings. The fault is marked by a crushed zone, mainly of sole rock, some 10 feet thick.

[2] Crickmay, G. W., Status of the Talladega series in southern Appalachian stratigraphy: Geol. Soc. America Bull., Vol. 47, pp. 1371–1392, 1936.

At Shelby, the Newala strikes north-northeast and is flexed into an anticline overturned to the southeast, with the northwest limb parallel to and dipping under the fault surface. The deformation attendant upon the thrusting was apparently taken up entirely by the Talladega, as there is no evidence of fracturing or small scale plastic deformation in the Newala.

LIMONITE ORES.

Distribution of the Ores.—The limonitic ore at Shelby occurs in two horizons; an upper consisting of transported red, compact, loamy clay with small rounded lumps of limonite, and a lower of residual clay containing large boulders and slabs of limonite and angular fragments of vein quartz. Locally these horizons are separated by lenses of white to buff sandy clay with small angular quartz fragments and widely scattered small, pea-sized lumps of limonite. The intervening sandy and clayey material has been regarded by Butts as a continuous layer, but the present study discloses that the sandy clay forms a discontinuous layer or recurrent lenses.

The two horizons of limonitic ore form a double blanket on the Newala limestone where the overthrust cover of Talladega has been stripped away by erosion and thus the ore-bearing area appears as a re-entrant projecting into the Talladega. The ore in the upper limonitic horizon has been designated as lump or float ore and is scattered irregularly through the red loam and clay for a thickness of 12 feet. In places it forms distinct lenses of tightly cemented material in a matrix of loose rounded pebbles of limonite but the greater part of the lump ore occurs as small rounded to angular fragments slightly larger than pea size. Butts [3] has reported that this ore averages 52 percent iron and that one ton of ore is contained in three to four cubic yards of material.

The white to reddish-orange clay and sand that lies immediately beneath the upper ore blanket contains small quantities of lump ore and many angular to rounded quartz pebbles in a matrix of irregularly interbedded sand and clay. The lens-like form of the sandy clay layer is evidenced by numerous occurrences of the upper lump-ore blanket resting directly on the lower, residual clay, ore bed. The average thickness of the intermediate "barren" clay and sand is about 10 feet.

The lower ore bed which rests directly on the Newala limestone consists of red to orange clay with streaks of limonite powder, scattered rounded pebbles of limonite, some sand and angular quartz fragments, and sporadically distributed large, slabby to rounded, more or less concretionary masses of spongy and porous limonite. The slabs and rounded concretionary masses, which may measure up to 3 or 4 feet in long dimension, are known locally as "dornicks." The thickness of the lower bed ranges from 15 to 25 feet.

Mode of Origin.—The localization of limonitic ore in the Shelby area is obviously governed by stratigraphic and structural controls. As stated earlier, the Talladega contains an abundance of small pyritiferous quartz veins which are conspicuous not only in the region around Shelby but elsewhere in the Talladega of Alabama and northwest Georgia. In the Shelby area, the

[3] Butts, Charles, op. cit., p. 217.

Newala which is a dense, fine grained, unfractured rock resistant to the movement of groundwater, has been overridden by the Talladega. With the regional uplift of the area through the activity of the Appalachian orogeny and subsequent epeirogenic uplifts, weathering and erosion of the Talladega ensued. As a result of weathering, the pyrite in the Talladega was converted to ferrous sulfate and sulphuric acid and the ferrous sulfate in turn oxidized to ferric sulfate. The downward moving ferric sulfate solutions carrying iron in solution by the presence of sulphuric acid, eventually reacted with the calcium carbonate of the Newala limestone. Neutralization of the acid by the limestone precipitated ferric hydroxide or limonite. Direct hydrolysis of the ferric sulfate would be responsible for the spongy structured limonite. So far as is known, no siderite has been seen at Shelby, but a siderite stage may have been present nevertheless, and later oxidation of the siderite would result in limonite.

The large slabby and rounded masses of spongy limonite ore in a clay matrix which is directly above the Newala are residual. The upper ore horizon of lump or float ore has most probably been eroded and transported from the lower horizon at an upstream source. The intermediate, essentially barren lenses of clay and sand above the lower horizon represent fluviatile material deposited by an aggrading stream. The coarse to fine elastic débris derived from the Talladega was first dropped, and later the limonite was carried down after erosion had reached the residual ore resting on the Newala.

Age.—The formation of limonite ore in the Shelby area must have required a considerable length of time. Burchard [4] and Eckel [5] believe the brown ores of Alabama to be Cretaceous and Tertiary; the ore in the Birmingham area being regarded by Burchard as Tuscaloosa (upper Cretaceous), and that in the Brookwood quadrangle as post-Cretaceous. Adams,[6] in a review of the work of Burchard and Eckel, concludes that the ores are post-Paleozoic, and are for the most part of Tuscaloosa age, and to a lesser extent, Eocene.

The residual ore of the lower horizon at Shelby is surely post-Paleozoic, for it was not formed until after the Appalachian orogeny had prepared the structural setting, and weathering and erosion had penetrated deeply into the overthrust Talladega. It is not certain just when the iron-bearing solutions came in contact with the Newala limestone and the ore began to form, but the ore formation probably continued over a very long interval and may still be taking place where geologic conditions are favorable for accumulation.

The overlying sand and clay zone and the transported ore in the upper horizon are younger than the bottom residual ore zone; the intermediate sand-clay zone being an erosional product of the Talladega, and the upper lump or float ore zone a product of upstream erosion of the lower ore horizon. Although Butts [7] suggests that the intermediate sand and clay zone may be

[4] Burchard, E. F., Iron ore in the Brookwood Quadrangle, Alabama: U. S. Geol. Survey Bull. 260, pp. 321–334, 1905.

[5] Eckel, E. C., Origin of the ores in iron ores, fuels and fluxes of the Birmingham Dist., Ala.: U. S. Geol. Survey Bull. 400, pp. 154–160, 1910.

[6] Adams, G. I., The occurrence and age of certain brown ores in Alabama and adjacent states: Econ. Geol., Vol. 23, No. 1, pp. 85–91, Jan. 1928.

[7] Butts, Charles, op. cit., Montevallo-Columbiana folio, p. 17.

Tuscaloosa, there is actually very little similarity between it and the fairly wide exposure of Tuscaloosa 9 miles to the southwest. The age of the two transported horizons cannot be determined accurately but such alluvial filling could have taken place from late Tertiary to the present.

OTHER LIMONITE AREAS.

Limonitic ore formed under varied geologic conditions is common in Alabama and northwest Georgia. Two deposits, one in the Chulafinne district, Clay and Cleburne Counties, Alabama, and one in Polk County, Georgia, are worthy of note because their geologic occurrence and origin are not unlike the Shelby ores.

The ores in the Chulafinne district have been described by Huddle [8] as a replacement deposit in pyrite-bearing Talladega. There is apparently no underlying limestone to act as a precipitating agent and trap as in the Shelby area, but the schistose rocks themselves have seemingly held the iron released by the oxidation of the pyrite. As at Shelby it was the pyrite in the overthrust Talladega that supplied the iron for the limonitic ore.

The limonite deposits between Cedartown and Rockmart, Polk County, Georgia, which were being worked in the summer of 1948, have a geologic setting very similar to that at Shelby, the only difference being that pyritiferous Rockmart slate (possible Carboniferous age) unconformably overlies the Newala. The Cedartown-Rockmart deposits have been described by McCallie [9] who has identified them as residual accumulations on limestone with the ore having formed as bog ore in swamps on the upper limestone surface in Tertiary time. However, the presence of pyrite-bearing argillaceous rock overlying a fine grained, impervious limestone suggests that the Cedartown-Rockmart deposits may have originated in the same way as the Shelby deposits.

SUMMARY AND CONCLUSIONS.

The limonite deposits at Shelby, Alabama, occur between an overthrust mass of pyrite-bearing Talladega and an underlying stratum of fine-grained, impervious Newala limestone. Oxidation of the pyrite during weathering liberated solutions of ferrous sulfate and sulphuric acid and the ferrous sulfate in turn oxidized to ferric sulfate. The ferric sulfate solutions after downward migration to the level of the limestone were neutralized and limonite was formed. Limonite masses built up by accretion within the residual clay of the limestone and Talladega, but continual downward movement of the iron-bearing solutions was arrested by the impervious Newala limestone. The barren horizon of sand and clay over the residual limonite zone and the surface capping of lump and float ore represent fluviatile deposits transported from an eroded mass of weathered Talladega and residual limonite in an upstream direction. Other deposits in Alabama and Georgia indicate a similar method of origin within an analagous geologic environment.

[8] Huddle, J. W., Brown Iron Ore of the Chulafinne District: Alabama Geol. Survey Circular 17, 1941.

[9] McCallie, S. W., Iron ores of Georgia: Georgia Geol. Survey, Bull. 10–A, 1900.

It is suggested that future prospecting for limonite in the Shelby district and other regions of similar geologic situation be confined to areas of the Newala limestone that carry or have carried a cover of pyritiferous Talladega or similar argillaceous, pyrite-bearing rock. Drilling should be directed down the dip of the contact zone of the two formations to prospect the lateral extent of the lower residual ore horizon.

ACKNOWLEDGMENTS.

The writer wishes to express his gratitude to Mr. Knox Kershaw of the Shelby Sand and Ore Company for permission to examine the Shelby property and to publish this paper, and to Professor A. L. Anderson of Cornell University, for his kindness in reading the manuscript and in offering helpful suggestions.

DEPARTMENT OF GEOLOGY,
VIRGINIA POLYTECHNIC INSTITUTE,
BLACKSBURG, VIRGINIA,
January 3, 1949.

VESTIGIAL ZINC IN SURFACE RESIDUUM ASSOCIATED WITH PRIMARY ZINC ORE IN EAST TENNESSEE.[1]

H. E. HAWKES AND H. W. LAKIN.

ABSTRACT.

A series of samples of residual clay at the Friends Station zinc deposit, Tenn., was collected and analyzed for zinc. Results indicate that residuum containing 0.05 percent Zn and more is the product of weathering of limestone and dolomite containing zinc mineralization. Chemical analysis of residual clays for zinc shows promise as a method of prospecting for zinc in the limestone valleys of the southern Appalachians.

INTRODUCTION.

In December 1947, a series of samples of residual clay was collected by the senior author at a locality near the west end of the Friends Station zinc deposit, about six miles southwest of Jefferson City and 18 miles northeast of Knoxville, Tenn. Samples were analyzed for zinc by the junior author, using a rapid semi-quantitative field method described elsewhere in this issue of the Journal.[2]

The purpose of the study was two-fold: first, to discover whether zinc-rich areas occur in surface residuum derived from the weathering of calcareous rocks containing zinc minerals; and second, to determine whether the rapid test could be used effectively under field conditions for outlining such zinc-rich areas if they were found. The Friends Station area was selected because the geological environment was well known, the zinc deposit had been systematically blocked out by drilling, and the surface had not been disturbed by excavations or buildings.

This project is part of a continuing program of research by the U. S. Geological Survey on methods of prospecting by chemical and biochemical studies of soils, vegetation, and water.

Acknowledgments.—The authors are indebted to Mr. H. A. Coy and Mr. C. R. L. Oder of the American Zinc Co. of Tennessee, who made available the records of diamond-drill holes in the Friends Station area and who obtained the permission of their company to publish the data contained in this report; and to Mr. R. A. Laurence and Mr. Arnold L. Brokaw of the U. S. Geological Survey, who reviewed the manuscript and made many helpful suggestions during the course of the project.

GEOLOGY.

The Friends Station zinc deposit is within the Mascot-Jefferson City zinc district, in the great valley of East Tennessee. The geologic structure of the

[1] Published by permission of the Director, U. S. Geological Survey.

[2] Lakin, H. W., Stevens, R. E., and Almond, H., Field method for the determination of zinc in soils: Econ. Geol., vol. 44, pp. 296–306, 1949.

district is dominated by thrust slices striking generally east-northeast and dipping gently to the southeast.[3] The rocks within the thrust slices are predominantly limestones and dolomites of Cambrian and Ordovician age dipping generally from 10° to 50° to the southeast. The structure is complicated locally by folds and flexures formed either before or during the period of thrusting. The principal zinc deposits of the district are confined to a single formation, the Lower Ordovician Kingsport limestone of the Knox group. The thickness of the Kingsport limestone in the area under study is about 400 feet.

The dominant ore mineral is sphalerite. Pyrite occurs locally, but lead and copper minerals are generally absent.

The zinc deposits in the immediate vicinity of the sampled area occur as a system of tabular shoots conformable to the bedding which here strikes east-west and dips on the average 14° to the south. At one locality, minor occurrences of sphalerite of no economic importance have been found in the overlying Mascot dolomite.[3] Except for data from diamond-drill holes, the only direct indication of mineralization in the Kingsport near Friends Station was a single small zinc carbonate prospect (Fig. 1).

The Friends Station area is characterized by surface drainage, with only local development of sink holes and karst topography. The mineralized zone lies parallel to a gentle southerly slope dissected in places by gullies to depths up to 30 feet. Almost all the area is under cultivation at the present time.

WEATHERING AND SOILS.

Following customary soils terminology[4] ". . . the principal horizons of the soil profile are designated as A, B, and C. Taken together, the A and B horizons are referred to as the solum which represents the true soil, produced by soil-building processes from weathered materials and in which biological activities take place. The designation C refers to the parent material or unconsolidated weathered rock directly under the solum." In the southern Appalachians, the A horizon, or topsoil, is characterized by an impoverishment in colloids and bases and an enrichment in organic matter. The B horizon, or subsoil, usually has a higher content of clay minerals than either the A or C horizons; in limestone soils of the southern Appalachians, however, the clay content of the B horizon may under certain conditions be less than that of the C horizon. In limestone terrains the C horizon is the residual material, or residuum, resulting from the weathering of calcareous rocks lying beneath the horizons where soil forming processes have been active. The term "profile" in soils terminology refers to the vertical section through all the layers or horizons of loose materials from the surface to the unweathered parent rock.

The term "suboutcrop" in the present discussion refers to the trace of a geologic feature on the surface of bedrock beneath the residuum. If the residuum were removed, a suboutcrop would appear at the surface as a conventional outcrop.

[3] Bridge, Josiah, Geologic map and structure sections of the Mascot-Jefferson City zinc mining district, Tennessee: Tennessee Div. Geology, 1945.

[4] Kellogg, C. E., Soil survey manual: U. S. Dept. Agr., Misc. Pub. 274, p. 77, 1937.

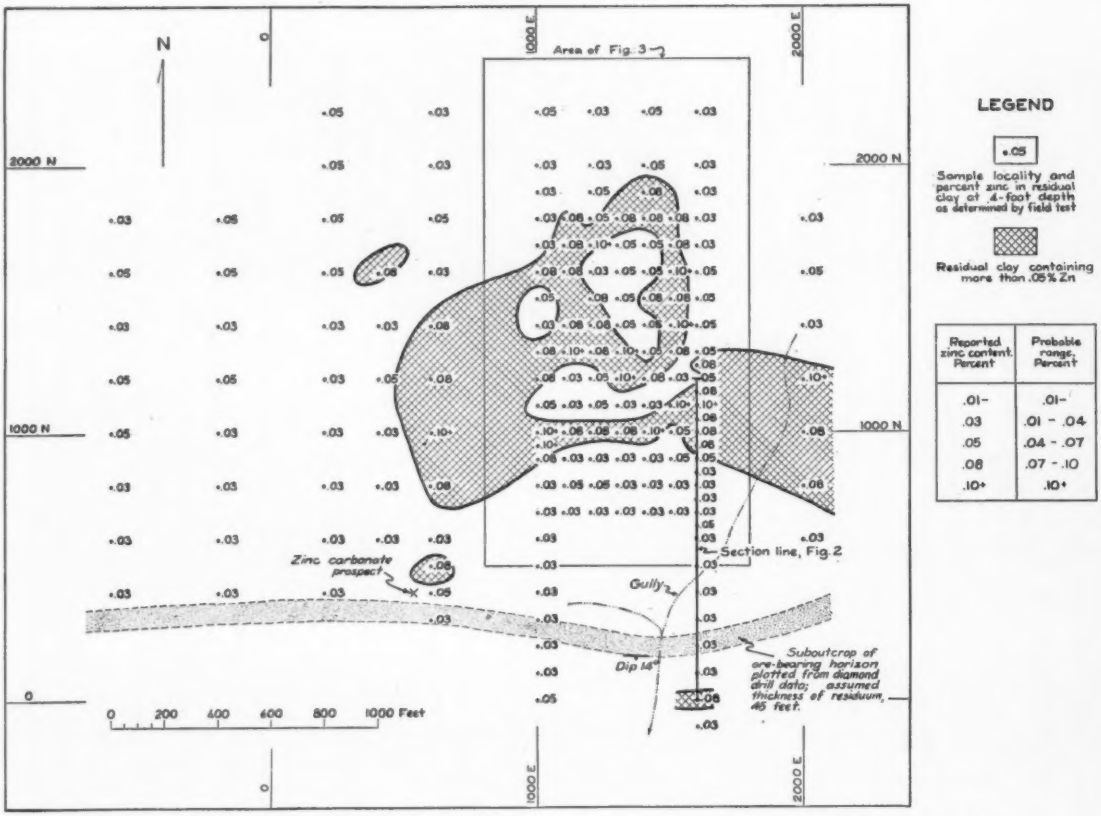

FIG. 1. Plan showing zinc content of residual clay, Friends Station zinc deposit, Jefferson County, Tennessee.

"Vestigial" structures in residuum are relics of primary structures in the parent rock, and are characterized by variations in structure, texture, mineralogy, or chemical composition. Vestigial bedding in the residuum at Friends Station is readily discernible in the field by variations in texture and color. Zinc-rich zones in the residuum, detectable only by chemical analysis, have been interpreted as vestigial after primary zinc deposits. The exposure of a vestigial structure in the residuum is referred to as an "outcrop" of that vestigial structure.

Figure 2 is a diagrammatic section showing the relation of the suboutcrop of the mineralized zone at Friends Station to certain vestigial structures in the residuum.

Analytical data in this paper are expressed in percentages rather than parts per million to avoid ambiguity as to the number of significant figures in the data.

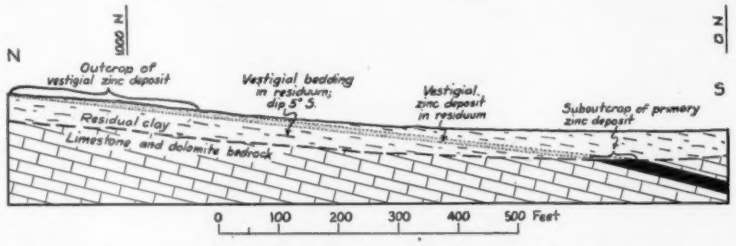

FIG. 2. Diagrammatic section along line 1600 E. (See Fig. 1 for location.)

Residuum.—The thickness of residuum at Friends Station, from the records of nine diamond-drill holes in the immediate vicinity of the sampled area, varies from 15 to 71 feet, and averages about 45 feet. The only outcrops of bedrock are in the gully bottoms. The fresh residuum, or C horizon, has been described as a heavy, stiff, plastic and sticky reddish-yellow clay with red, yellow, and olive mottling.[5] It varies locally from heavy, relatively impervious clays to somewhat more pervious silty or sandy clays. Fragments of chert occur throughout the residuum, and make augering difficult. Exposures of residuum in the vertical walls of the deep gully in the southern part of the sampled area show conspicuous vestigial bedding. In some of the exposures of residuum in the gully the vestigial bedding is very irregular, and individual horizons rarely can be followed for more than about ten feet. In other exposures it is remarkably even, and horizons can be traced fifty feet or more. Measurements on three of the best exposures of uncontorted vestigial bedding all indicate a dip of about 5° S, which is much flatter than the dip of the underlying rock formations. The flattening of the dip is interpreted as the effect of the reduction in volume in the weathering of limestone to form clay. The relative values for dip in bedrock and residuum indicate that at Friends Station approximately three volumes of limestone have weathered to form one volume of clay.

[5] Moon, J. W. *et al.*, Soil Survey, Jefferson County, Tennessee: U. S. Dept. Agr., Series 1935, No. 20, 1941.

FIG. 1. Plan showing zinc content of residual clay, Friends Station zinc deposit, Jefferson County, Tennessee.

Soils.—The predominant soil in the area of Figure 1 is Dewey silt loam. For a detailed description of this soil, the reader is referred to the U. S. Department of Agriculture Soil Survey Report on Jefferson County, Tenn.[5] Most of the samples collected at a depth of 4 feet are apparently from the lower part

TABLE 1.

ZINC CONTENT OF RESIDUAL CLAY AT DEPTHS UP TO 6 FEET; LINE 1600 E.

Station	Surface	2 feet percent	4 feet percent	6 feet percent
2400 N	.03	.03	.03	.03
2200 N	.03	.03	.03	.03
2000 N	.03	.03	.03	.03
1900 N	.03	.03	.03	.03
1800 N	.03	.03	.03	.08
1700 N	.03	.03	.03	.03
1600 N	.03	.03	.05	.03
1500 N	.03	.03	.05	.05
1400 N	.03	.05	.05	.03
1300 N	.03	.03	.05	.10+
1250 N	.03	.05	.08	.10+
1200 N	.03	.03	.05	.08
1150 N	.03	.05	.08	.10+
1100 N	.03	.08	.10+	.10+
1050 N	.03	.05	.08	.05
1000 N	.03	.08	.08	.08
950 N	.03	.08	.08	.08
900 N	.03	.05	.05	.08
850 N	.03	.03	.03	.03
800 N	.03	.03	.03	.03
750 N	.03	.03	.03	.03
700 N	.03	.03	.03	.03
650 N	.03	.03	.05	.03
600 N	.03	.03	.03	.03
500 N	.03	.03	.03	.03
400 N	.03	.03	.03	.03
300 N	.03	.03	.03	.03
200 N	.03	.03	.03	—
100 N	.03	.03	.03	.05
0	.05	.03	.08	.08
100 S	.03	.03	.03	.03
200 S	.03	.03	.03	.03
400 S	.03	.03	.03	.03
600 S	.03	.03	.03	.05
800 S	.03	.03	.03	.05
1000 S	.03	.03	.03	.05
Average	.031	.036	.045	.050

Analytical method described by Lakin, Stevens, and Almond.[2]

of the B horizon, which differs from the C horizon mainly in the absence of conspicuous mottling.

Soil erosion is common in cultivated fields, and in several parts of the sampled area the upper soil horizons have been completely removed. No evidence of soil creep of any magnitude was found either in examination of vestigial structures in the gully walls or by study of the distribution of the zinc.

Evidence of surface wash, locally spreading a thin sheet of alluvium over indigenous topsoil, was observed at a few of the sample stations.

Chemical analyses of a typical profile of Dewey silt loam near Russellville, Ala., show a significant increase in alumina, ferric oxide, and magnesia with depth, a decrease in silica, potash, and soda, and no significant variations in lime, titania, manganese, phosphate, or sulfate.[6] The silt content (0.05 to 0.002 mm.) decreases and the clay content (less than 0.002 mm.) increases with depth in the profile. The data of Table 1 indicate that the zinc content of the Friends Station soils tends to increase with depth in the soil profile, paralleling the content of alumina, iron, magnesia, and clay-sized particles in the typical profile. No study was made of the form in which the zinc is held in the residual clay.

Locally the B horizon at Friends Station contains abundant small concretions of manganese oxide, one of which was found to contain about 0.4 percent Zn. The zinc content of the clay matrix of this nodule is about 0.05 percent.

SAMPLING.

Field Procedure.—Sample stations were laid out on an arbitrary coordinate system surveyed by tape and compass. Sample holes were bored by hand with a light soil auger to the desired depth, and the sample collected from the clay adhering to the auger bit at that depth. The sample, consisting of three or four small fragments of clay weighing in all about five grams, was placed in a labeled manila envelope and transmitted to the chemist for analysis.

Auger.—The soil auger was constructed of 3-foot sections of ⅜-inch pipe fitted with a T-handle and a 1¼-inch wood bit. One man can put down from 20 to 30 4-foot holes per day, depending on the nature of the material.

Size of Sample.—Within reasonable limits, the size of the sample was found to make relatively little difference in the quality of the data. Table 2 shows laboratory determinations of the zinc content of nine dried, ground, and quartered bulk samples compared with similar analyses of grab samples collected at the same stations. About 500 grams of material were used in each of the bulk samples in this experiment, whereas only about 5 grams were used for the individual grab samples. The variation in values obtained by the different sampling procedures is well within the limit of error of the chemical procedure, so apparently there is no significant loss in accuracy of data by substituting grab samples for bulk samples. The outstanding advantage of the grab sampling technique is the saving of the excessive amount of time and work required in the drying, grinding, and quartering of large samples.

Depth.—Four feet was found to be the optimum depth of sampling. Samples collected at the surface or at a depth of only 2 feet were usually lower in zinc content, indicating a removal of zinc by processes of soil formation. Figure 3 shows comparative maps of the same area sampled at both 2 and 4 feet, and illustrates the much better definition of the zinc-rich area obtained by sam-

[6] Alexander, L. T., Byers, H. G., and Edgington, G., A chemical study of some soils derived from limestone: U. S. Dept. Agr. Tech. Bull. 678, 28 pp., 1939.

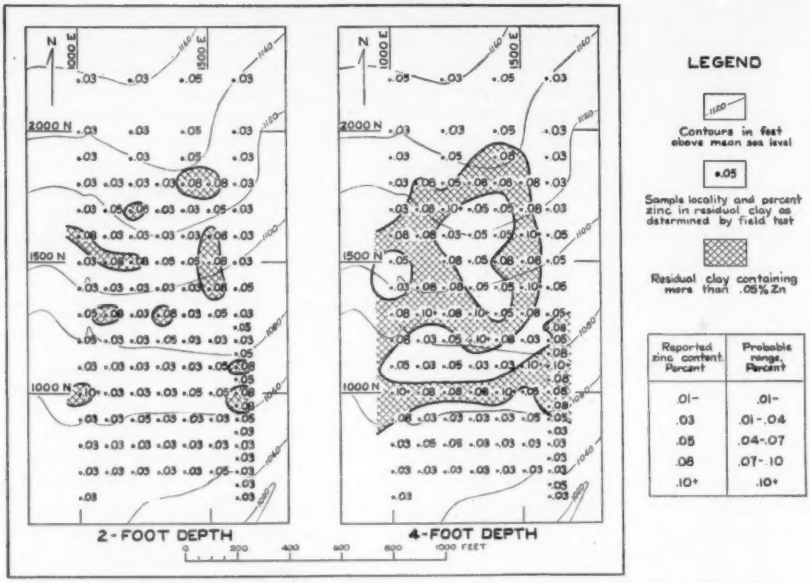

FIG. 3. Comparative plans showing variation of zinc content of residual clay with depth below surface. (See Fig. 1 for location.)

pling at 4 feet. Of the 105 stations shown in Figure 3, the reported zinc content of samples taken at 4 feet was higher than samples at 2 feet at 57 stations, the same at 41 stations, and lower at 7 stations. Areas of high zinc content in

TABLE 2.

COMPARISON OF ZINC CONTENT OF GRAB SAMPLES AND BULK SAMPLES.
(Analyst, Laura E. Reichen, Geological Survey.)

Sample station	Depth (feet)	Zinc content in percent	
		Grab sample	Bulk sample
950 N; 1000 E	2	.20	.20
1000 N; 1000 E	2	.16	.16
1300 N; 1200 E	4	.087; .078	.090; .092
1000 N; 1400 E	4	.07	.078
900 N; 900 E	2	.057	.067
900 N; 1000 E	4	.053	.050
800 N; 1200 E	4	.038	.037
800 N; 1000 E	2	.027	.026
850 N; 1250 E	2	.0215	.022

Analytical method described by Holmes.[7]

[7] Holmes, R S, Determination of total copper, zinc cobalt, and lead in soils and soil solutions: Soil Sci, vol. 59, pp. 77–84, 1945.

the 2-foot samples correspond roughly to eroded areas where the deeper soil horizons are closer to the surface. Table 1 shows the comparative zinc content of soil and residuum at depths to 6 feet, and indicates that very little additional information is gained by going deeper than 4 feet.

Contamination.—With proper precautions, contamination of samples from dirt and from contact with tools apparently is not a serious problem. A possible source of contamination was expected from zinc in mill tailings, which for a number of years has been sold by the local mines for agricultural lime and applied by the farmers to most cultivated fields. The maximum zinc content of tailings is reported to be about 0.5 percent. To increase the zinc content of an acre-foot of soil by 0.02 percent, which is the smallest variation reported in the field test, 70 tons of tailings of this composition would be required. An average of 1 ton per acre per year is the maximum amount of lime added in customary agricultural practice, so danger of contamination from this source would not be serious. Erratic results due to fragments of sphalerite from tailings material included in the soil samples would not be expected below plow depth.

Reproducibility of Data.—Both sampling and analytical techniques involve short cuts that would be questionable in a precise quantitative investigation. As an operating control on the adequacy of both sampling and analytical work, six or eight stations were systematically resampled each day, and the determined zinc content compared with previous data. In all, 76 samples were duplicated in this way, of which 47 pairs checked, 24 pairs differed by one analytical unit, and 5 pairs differed by two units.

RESULTS.

Figure 1 shows the distribution of zinc in the residuum at a depth of 4 feet. The approximate location of the suboutcrop of the zinc deposit is plotted from diamond-drill data furnished by the American Zinc Co. of Tennessee.

The area of zinc-rich residuum between 1000 E and 1600 E was sampled on a 100-foot isometric grid; elsewhere samples are more widely spaced and give a correspondingly more generalized picture of the distribution of zinc. The principal zinc-rich area is in the north-central and eastern sections of the map area, and extends off the map to the east for an unknown distance. The south boundary of this area lies about 600 feet north of the suboutcrop of the ore.

Table 3 shows data obtained from several deep auger holes put down on line 1600 E. One deep profile was cut in the vertical wall of the gully to a depth of 28 feet, directly over an outcrop of dolomite exposed in the channel of the gully. Below the zone of surface leaching, the zinc content of residuum from these holes is essentially constant, with the exception of the higher zinc content of samples near the bottom of the holes at 850 N and 600 N.

The normal zinc content of the residuum at Friends Station appears to be in the order of 0.03 percent. This is very high as compared with most soils, where the zinc content rarely exceeds 0.01 percent,[8] and may be the effect of

[8] Holmes, R. S., Copper and zinc contents of certain United States soils: Soil Sci. vol. 56, pp. 359–370, 1943.

widely disseminated sphalerite in the parent limestones. Zinc concentrations of 0.08 and 0.10 + percent, such as were found at Friends Station, represent a ten-fold excess of zinc over that occurring in normal soils.

Interpretation of Data.—Figure 2 shows on a diagrammatic cross section the apparent relation between the zinc deposit in the bedrock and zinc-rich residuum at the surface. If a uniform depth of residuum of 45 feet is assumed, it is seen that a line connecting the suboutcrop of the hanging wall of the mineralized zone and the south boundary of the zinc-rich area at the surface is roughly parallel to the dip of the vestigial bedding observed in the gully walls. The interpretation is made that the principal zinc-rich area in the residuum is a vestigial feature inherited from the chemical composition of the parent rock. More specifically, the rock that decomposed to form the zinc-rich residuum was

TABLE 3.

ZINC CONTENT OF RESIDUAL CLAY FROM DEEP AUGER HOLES.

Depth in feet	Sample station and zinc content (percent)				
	1600 E 2000 N	1600 E 1300 N	1600 E 850 N	1600 E 600 N	1415 E 115 N [1]
0	.03	.03	.03	.03	.03
2	.03	.03	.03	.03	.03
4	.03	.05	.03	.03	—
6	.03	.10+	.03	.03	—
8	.03	.10+	.03	.03	—
10	.03	.10+	.05	.03	.03
12	.03	.10+	.03	.05	.03
14	.03	.10+	.05	.05	.03
16	.03	.10+	.08	.05	.03
18	.03	.10+	.08	—	.03
20	.03	.08	.08	—	.03
22	—	.10+	—	—	.03
24	—	—	—	—	.03
26	—	—	—	—	.03
28	—	—	—	—	.03

[1] Sample taken from the vertical wall of a gully directly over an outcrop of dolomite in the gully channel.

Analytical method described by Lakin, Stevens, and Almond (1949).

an up-dip extension of the present ore body. Thus even though no outcrops of primary ore occur in the area, the outcrop of vestigial ore in the residuum is very definite.

The deep auger hole located at 1600 E, 850 N was put down to intersect the hanging wall of the vestigial mineralized zone and pass into zinc-rich residuum at depth. This hole passed into zinc-rich material at a depth of about 14 feet (see Table 3), considerably below what would be expected from the simplified projection in Figure 2. A 16-foot auger hole put down at 1600 E, 600 N for the same purpose passed into residuum containing 0.05 percent zinc at about 12 feet. It is probable that the vestigial bedding in residuum is draped over irregular pinnacles and sags in the bedrock surface, similar to those observed generally in limestone terranes of the southern Appalachians. If such

is the case, a corresponding irregularity of the vestigial mineralized zone in the residuum would be expected.

Figure 1 shows a fairly definite correlation between the zinc deposit and the highest zinc content in the residuum. Areas of residuum containing 0.05 percent zinc occur outside the principal zinc-rich area and probably reflect minor ore shoots bordering the main mineralized zone.

CONCLUSIONS.

Zinc-rich areas in the residuum were found in association with, and apparently genetically related to, a primary zinc deposit in the bedrock at Friends Station. The rapid test for zinc in soil material developed by the junior author is adequate for delineating these zinc-rich areas in the field, and gives promise of becoming a useful tool in zinc exploration.

GEOCHEMICAL PROSPECTING UNIT,
U. S. GEOLOGICAL SURVEY,
WASHINGTON 25, D. C.,
February 10, 1949.

FIELD METHOD FOR THE DETERMINATION OF ZINC IN SOILS.[1]

H. W. LAKIN, R. E. STEVENS, AND HY ALMOND.

ABSTRACT.

A method is described for the field estimation of total zinc in soils. A small sample of soil is fused with potassium bisulfate, the fused mass dissolved in water, buffered at pH 4 to 5.5 with acetate buffer, and sodium thiosulfate added to form complex ions with metals that might cause interference. Measured increments of the sample solution are added to a carbon-tetrachloride-dithizone solution, with vigorous shaking after each addition, until a standard color is obtained in the organic phase. Under favorable conditions up to 60 determinations per day can be made by one man. Comparisons of data obtained by the field method with accurate laboratory analyses of the same samples indicate that the method is sufficiently reliable for reconnaissance surveys.

INTRODUCTION.

THE development of a field method for the determination of zinc in soils was undertaken as a part of the program of the Geochemical Prospecting Unit, U. S. Geological Survey, in anticipation that a quick field test for zinc in soils may have important application in the evaluation of known zinc localities, as well as in the discovery of new deposits of the metal. The following is a discussion of the problem, a description of the method developed and tentatively adopted by the Unit, and a review of tests of its reliability both in the laboratory and in the field. Correlation of results obtained by the method to known zinc-bearing formations in Tennessee is described in another article in this Journal (5).[2]

The normal zinc content of soils is from .003 to .01 percent (30 to 100 parts per million) (7); a significantly higher zinc content approaching .1 percent (1000 parts per million) may be expected in soils genetically related to primary zinc deposits. The field test used should, therefore, measure values in this range of concentration.

The simplicity that may be attained in devising field methods for specific metals in soils is limited by several complicating factors inherent in the composition of soils. The analyst must assume that all of the interfering elements for any given method are present. A further complication is the presence in the soil of minerals of widely differing resistance to chemical attack. The heterogeneous nature of soil, both in texture and in chemical composition of individual particles, introduces a sampling problem that might best be met by making analyses of many samples. However, a field test must be simple to use, involve transport of a minimum of material and dangerous reagents, and be sufficiently rapid to permit the accumulation of a mass of data in a short

[1] Published by permission of the Director, U. S. Geological Survey.
[2] Figures in parentheses refer to Bibliography at end of paper.

time. In obtaining these conditions, accuracy may suffer and the method evolved may be only semiquantitative.

The field test for zinc described below is an attempt to realize the requirements for speed, mobility, positive identification of the element, and yet to mantain sufficient accuracy to classify soils into significant groups on the basis of their zinc content. With this method forty to sixty tests can be made in a day under field conditions. As it now stands, the procedure may be considered a working model which may be improved and simplified or replaced by a more desirable technique.

In the present study zinc is rendered soluble by an adaptation of the potassium bisulfate fusion of Boggs and Alben (2). Although many minerals such as quartz and feldspar (1) are not decomposed by fusion with potassium bisulfate, it suffices to extract essentially all the zinc from zinc-bearing minerals commonly present in the soil. Sodium carbonate (9) attacks these minerals, but its use entails higher temperatures and use of platinum fusion vessels deemed impractical for field use. Mineral acids (6) are also effective in dissolving zinc from most minerals, but their use involves a longer time in decomposing samples and more difficulties in safe transport.

For the isolation and estimation of traces of zinc after it has been dissolved, carbon tetrachloride extraction of the zinc compound with dithizone (diphenylthio-carbazone) has largely replaced classical methods involving hydrogen sulfide. It does not appear appropriate to discuss the many reactions of dithizone here, as there are many excellent published discussions of this reagent. One of the best is to be found in chapter 4 of "Colorimetric Determinations of Traces of Metals" by E. B. Sandell (11). The method of isolation and estimation is an adaptation of Fischer and Leopoldi's mono-color procedure (4) and Sandell's mixed color method (10). Both methods are discussed by Sandell in chapter 24 of the book mentioned above.

Briefly, the method of estimating zinc is based upon the fact that at pH of 4 to 5.5, sodium thiosulfate largely prevents the reaction of copper, mercury, silver, gold, bismuth, lead, and cadmium with dithizone while permitting that of zinc to proceed. Under these conditions zinc forms the keto complex with dithizone which is soluble in carbon tetrachloride giving a solution of red-violet color. The color of the carbon tetrachloride solution varies from green (unreacted dithizone), through blue, purple-violet, to red-violet with increasing quantities of zinc.

REAGENTS.

Potassium Bisulfate.—Analytical quality is satisfactory provided the color standards are made with approximately the same amount of the fused salt in the solution as is used with each sample. For very careful work prepare the bisulfate by washing an alkaline solution of potassium sulfate with dithizone dissolved in carbon tetrachloride, acidify and evaporate to fumes of SO_3. A small excess of sulfuric acid over that required to form bisulfate is desirable, as organic matter in the soil is then more readily destroyed.

Water.—Redistillation through an all-pyrex still is desirable. It has been found, however, that the small resin demineralizers now on the market give

water of satisfactory purity. An improvised support containing renewal cartridges designed for the Bantam Demineralizer by Barnstead Still and Sterilizer Co., Inc., was used in this work.

Acetate Buffer.—Mix 5 volumes of 2 N sodium acetate with 2 volumes of 2 N acetic acid, and remove reacting heavy metals by shaking with 0.01 percent dithizone solution. Purification is not essential when color standards are prepared with the same amounts of reagent as used with the sample.

FIG. 1. A portable kit containing apparatus and reagents for making zinc test.

Sodium Thiosulfate.—50 grams of $Na_2S_2O_3 \cdot 5H_2O$ in 100 ml of water.

Standard Zinc Solution.—0.01 percent in dilute hydrochloric acid. Dissolve reagent-grade 30-mesh zinc in a slight excess of hydrochloric acid and dilute to volume. Prepare dilute solution containing 20 micrograms zinc per ml from the standard.

Carbon Tetrachloride.—Analytical quality can be used in the field. It is preferable, however, to purify reagent-grade carbon tetrachloride by distillation in an all-pyrex still.

Dithizone.—0.0025 percent (weight/volume) in pure carbon tetrachloride.

APPARATUS.

The equipment consists of a compact kit containing apparatus and reagents for making a few tests in the field, and a reserve supply of glassware and reagents and apparatus for purifying water. The kit is illustrated in Figures 1 and 2 and consists of the following:

FIG. 2. A portable gasoline stove and test tube rack for making fusions.

a. 20 pyrex test tubes, 18 × 150 mm, marked at 3, 10, and 11 ml.
b. 20 pyrex test tubes, 16 × 150 mm, marked at 5 ml.
c. 500 ml pyrex, glass-stoppered bottle for acetate buffer solution.
d. 500 ml pyrex, glass-stoppered bottle for dithizone solution.
e. 250 ml pyrex, glass-stoppered bottle for redistilled water.
f. 100 ml pyrex, glass-stoppered bottle for sodium thiosulfate solution.

g. 100 ml pyrex, glass-stoppered bottle for standard zinc solution.
h. 5 ml graduated pipette fitted with a stop cock at upper end.
i. 100 ml graduated cylinder or other suitable device in which to support pipette.
j. Lucite bar or any zinc-free material, with cavity of 0.05 ml drilled near one end.
k. Lucite bar or any zinc-free material, with cavity of 0.25 ml drilled near one end.

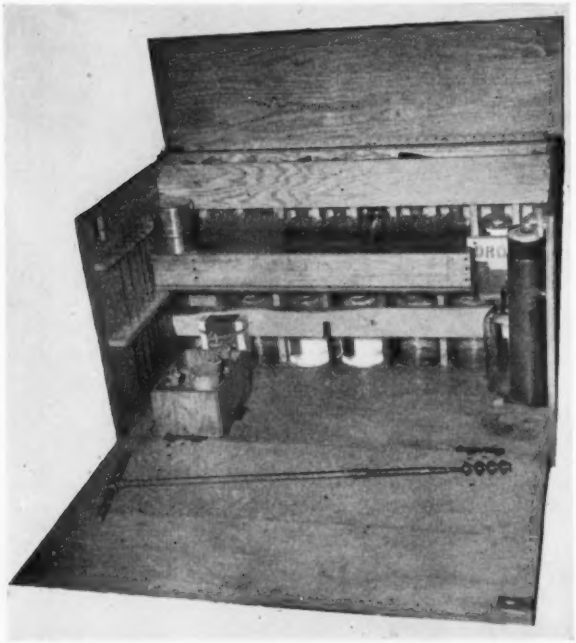

FIG. 3. A trunk for transporting stock reagents and supplies.

l. Agate or mullite mortar and pestle, outside diameter of mortar 3 inches.
m. 2 sieves, 2 mm mesh iron screen and 100-mesh cloth, 3½ in. diameter.
n. Aluminum receiver to fit interchangeably above sieves.
o. 1 small brush.
p. 1 small spatula.
q. 1 small (25 ml vol.) bottle for powdered potassium acid sulfate.
r. 1 stainless steel tablespoon.
s. 1 suitable metal carrying case, 16 × 8 × 8 inches, and fitted with suitable racks to fit above material into case.

All of the above materials were carried in the case shown in Figure 1. A portable Coleman stove and test tube rack for fusions are shown in Figure 2.

The reserve apparatus required is illustrated in Figure 3. A large trunk, 4 × 2 × 2 feet, opening in the front and top was used to transport reserve supplies of stock solutions, glassware, and solid reagents. The demineralizer for purifying water was installed in the trunk. This system permits the chemist to be reasonably independent of local chemical facilities for supplies. When large soil samples are taken, a 15-inch square iron sheet fitted with legs to set over the Coleman stove is useful for drying the samples. A wooden rolling pin, large sheets of wrapping paper, and a large spatula are also needed.

PROCEDURE.

Methods of Sampling.—Preliminary studies should be made at the locality under examination to determine how much care must be taken in obtaining representative samples. A preliminary study of the area examined in Tennessee (5) showed that three small pinches of soil taken from the inside of a soil auger curl gave results in general agreement with more elaborate sampling. The general procedure for sampling, which may be greatly simplified in most areas, is as follows:

Take at least one-half pound of soil and dry it. Break up clods with a wooden rolling pin, pass through a 2 mm-mesh sieve, quarter down by conventional procedure until three to five grams are obtained. Pulverize this small sub-sample in an agate or mullite mortar to an impalpable powder and take sample for analysis.

Preparation of Sample Solution.—Fill a lucite scoop, capacity 0.05 ml, with soil by tightly pressing the prepared soil into the scoop with a small flexible spatula. Wipe the outside of the scoop level with the spatula, and tap into a pyrex (18 × 150 mm) test tube. Add one scoop (lucite scoop, capacity 0.25 ml) of powdered potassium bisulfate to the soil sample and place in the test tube fusion rack. Place the fusion rack with six test tubes containing soils and one reagent blank on the Coleman pocket stove and heat for about 10 minutes or until the soil is essentially decomposed. If necessary add a little more potassium acid sulfate to effect the desired fusion. Remove, allow to cool, add 3 ml of water to each sample, and again heat until a milky suspension is obtained. Prolonged or too violent heating will cause excessive bumping and should be avoided. Add 7 ml of the acetate buffer solution and 1 ml of the sodium thiosulfate solution to each sample, stopper wtih a clean cork, shake thoroughly, and set aside to allow the suspension to settle and the solution to cool.

Estimation:

This step is essentially a titration. Place 5 ml of the .0025 percent dithizone solution in a pyrex test tube (16 × 150 mm). Add measured increments (1.0, 1.5, 2.0, 3.0, and 8.0 ml) of the solution prepared from a soil sample to the dithizone solution and shake vigorously for one minute between each addition, using a clean cork to close the test tube. Sufficient sample solution has been added when the color of the carbon tetrachloride layer matches a standard containing 5 micrograms of zinc, prepared as follows: Add

20 micrograms of zinc to the reagent blank carried through the fusion process, dissolve and buffer as above, and shake one-fourth of the solution with 5 ml of .0025 percent dithizone solution. Make new color standards frequently because the color fades rapidly.

The added increments of the sample solution correspond to zinc content of the soil samples as follows:

Ml of sample solution required to match standard	Probable zinc content %	Reported value (group value) %
1.0	0.10 and up	.1+
1.5	.07–.10	.08
2.0	.04–.07	.05
3.0 to 8.0	.01–.04	.03
excess of 8.0 ml.	under .01	.01–

EFFECT OF FOREIGN METALS.

A soil sample containing .038 percent zinc, .038 percent copper, and .12 percent lead was used to test the influence of excessive amounts of those metals which might be expected to affect the result for zinc. The data are presented in Table I. The presence of nickel and lead in amounts 20 times that of zinc had little effect in results by the field test. Cobalt and mercury increased the apparent values for zinc by 50 percent when present in amounts 20-fold that of zinc. Copper and cadmium increased the values for zinc by 75 percent when their concentrations were ten times that of zinc, the effect of cadmium being somewhat erratic. Of these metals, copper is the only one that might

TABLE I.

EFFECT OF FOREIGN METALS UPON THE ESTIMATION OF ZINC BY THE FIELD METHOD.

Soil + foreign metal	Zinc taken γ	Zinc found γ
Soil [1] (No. 47478) .05 gm	19	20
Soil (No. 47478) .05 gm	19	20
Soil + 100γ Copper	19	25
Soil + 200γ Copper	19	35
Soil + 500γ Copper	19	50
Soil + 100γ Cobalt	19	20
Soil + 200γ Cobalt	19	22
Soil + 400γ Cobalt	19	30
Soil + 100γ Nickel	19	20
Soil + 200γ Nickel	19	20
Soil + 400γ Nickel	19	20
Soil + 100γ Cadmium	19	25
Soil + 200γ Cadmium	19	35
Soil + 300γ Cadmium	19	30
Soil + 100γ Mercury	19	20
Soil + 200γ Mercury	19	25
Soil + 400γ Mercury	19	30
Soil + 100γ Lead	19	20
Soil + 200γ Lead	19	20
Soil + 300γ Lead	19	20
Soil + 100γ Zinc	119	125
Soil + 200γ Zinc	219	250

[1] Composite soil sample from Gold Hill, N. C. The soil contains .038 percent of zinc, .038 percent copper and .12 percent lead.

reasonably be expected to occur in sufficient quantities to affect the zinc values adversely. Iron and aluminum are present in soils as major constituents, but their effect on the method is not serious. Data obtained on soils of widely different manganese content did not indicate interference by this element.

TESTS OF RELIABILITY OF THE FIELD METHOD.

The tests reported in Table II were performed in the laboratory under ideal conditions. Results by the field method are given in the second column, and results by the dithizone method of Holmes (8) are in the last column of the table. The italicized zinc values in the last column are for soils that the field method failed to classify properly; italicized figures indicate that the field method was in error by a single group; italicized figures in parentheses indicate an error of two groups. Of the 69 soils, 13 percent (1 out of 8) did not belong in the group assigned to them by the field method, and 2 percent (1 out of 69) were misplaced two groups.

TABLE II.

COMPARISON OF FIELD AND LABORATORY METHODS ON SOILS FROM VARIOUS SOURCES.

No. of samples	Field method Probable zinc content in percent		Laboratory method Zinc content of each soil in percent
	Range	Value reported	
13	Under .01	.01 −	.0010, .0011, .004, .004, .0045, .0045, .005, .0055, .0055, .0058, .0066, .008, .01
32	.01–.04	.03	*.0072*, .010, .014, .014, .014, .014, .015, .016, .017, .019, .019, .021, .023, .024, .025, .027, .028, .028, .028, .028, .031, .033, .033, .036, .036, .038, .039, .040, .042, *.052*, *.053*, *.055*
12	.04–.07	.05	*.031*, *.039*, .040, .041, .043, .047, .047, .056, .060, .068, *.076*, *.087*
5	.07–.10	.08	.080, .084, .084, .084, .084
7	.10–up	.1 +	(*.060*), .12, .12, .13, .16, .16, .36

A trial area near Friends Station, Tenn., was selected for checking the performance of the method under field conditions. About 100 samples were tested outdoors at the time of collection, and about 550 more determinations were made in a tourist cabin near the sampling area. A discussion of the significance of these field analyses in geochemical prospecting will be found in another paper in this journal (5). Of these soils, 64 were analyzed later in the laboratory, using the Holmes method. The results are given in Table III. Fourteen out of the 64 samples (22 percent) were in error by at least one group, and 1 out of 64 (2 percent) in error by two groups.

It appears that 75 to 85 percent of the samples examined by the field method and subsequently checked by careful analyses were correct by the field classification. Obviously, with so low a correlation between the reported and true

values, one must not place too great reliance on single determinations. It should be kept in mind that the degree of precision generally obtainable in trace analysis is much less than that obtainable in most macrochemical determinations. Under carefully controlled conditions, most methods for trace analysis give results within about 5 to 10 percent of the true value for a single determination (12). More erratic results should be expected for field estimations.

TABLE III.

COMPARISON OF TESTS IN THE FIELD WITH SUBSEQUENT LABORATORY ANALYSIS.

No. of samples	Field method Probable zinc content in percent		Laboratory method Zinc content of each soil in percent
	Range	Value reported	
0	.01–	.01	—
24	.01–.04	.03	.020, .021, .022, .022, .022, .022, .026, .026, .027, .027, .028, .029, .030, .030, .030, .032, .034, .035, .038, .039, .040, .040, *.047*, *.062*
14	.04–.07	.05	*.022*, *.027*, *.037*, *.038*, .045, .046, .048, .050, .053, .057, .061, .065, .068, *.076*
13	.07–.10	.08	*.050*, *.057*, *.067*, .070, .070, .080, .087, .087, .091, .092, .098, *.11*, *.11*
13	.10–up	.1+	(*.053*), *.078*, .13, .13, .14, .16, .16, .16, .16, .19, .20, .20, .40

If little reliance can be placed upon any single value, how much reliance can be placed upon a group of these values? To answer this question the variance between the groups represented by .03, .05, and .08 was tested against the variance within these groups. These three groups were selected because they represent equal increments in range of zinc content. The analysis of variance [3] is shown in Table IV. An F value [4] of 56 was obtained where only 8.2 is required for significance at odds of 999:1.

TABLE IV.

ANALYSIS OF VARIANCE FROM TRUE VALUES IN RESULTS OF FIELD TESTS FOR ZINC.

Source of variance	Degrees of freedom	Mean square
Between groups 2, 3, and 4	2	.011007
Within groups 2, 3, and 4	48	.000195
Total	50	

[3] The analysis of variance used in this study is described fully on pages 49 and 50 of Brownley's "Industrial Experimentation" (3).

[4] The variance ratio, F, is equal to the mean square between groups divided by the mean square within groups or $\frac{0.011007}{0.000195} = 56$ for $N_1 = 2$ and $N_2 = 48$. Tables have been prepared for significance levels of F values for various N_1 and N_2 values. In any particular analysis, the larger the calculated value of F, the more certain it is that the two variances concerned are significantly different.

This means that the chance of there being no real differences between the means of groups is very much less than one in a thousand and for all practical purposes amounts to a certainty that there is a real difference between the groups.

Although single determinations are of low reliability, a large number of determinations give a high degree of certainty to a classification. To illustrate,

TABLE V.

COMPARISON OF FIELD TESTS WITH ZINC CONTENT OF SOIL COLLECTED ALONG LINE 1600 E AT 6 FOOT DEPTH, FRIEND STATION, TENNESSEE.

Sample location on line 1600 E	Field method Value reported %	Laboratory method %
1000 S	.05	.046
800 S	.03–.05 [1]	.035
600 S	.05–.03	.05
400 S	.03–.03	.04
200 S	.03	.022
100 S	.03	.034
0 N [2]	.08	.11
100 N	.05–.05	.068
200 N	.03	.028
300 N	.03	.047
400 N	.03	.026
500 N	.03	.020
600 N	.03–.03	.030
650 N	.03–.03	.062
700 N	.03	.032
750 N	.03	.039
800 N	.03–.03	.021
850 N	.03–.03	.030
900 N	.08	.080
950 N	.08	.098
1000 N	.08	.11
1050 N	.05–.05	.061
1100 N	.1+	.14
1150 N	.1+	.13
1200 N	.08–.08	.092
1250 N	.1+	.13
1300 N	.1+–.1+	.16
1400 N	.05–.03	.048
1500 N	.05	.076
1600 N	.05–.03	.065
1700 N	.03	.029
1800 N	.05–.08	.045
1900 N	.03	.030
2000 N	.03–.03	.027
2200 N	.03	.040
2400 N	.03	.022

[1] Second field-test values obtained on a second soil sample collected in close proximity to the original sample. Only the original samples were analyzed by the Holmes method.
[2] Sample collected at depth of 4 feet.

if one collected a single sample in a small field and obtained a zinc value of .08, the value by itself would have little significance, but if one then collected 50 more samples within the field and found a pattern of .08 values developing around the original sample, the certainty of the existence of an actual .08 area would be very high indeed.

A confirmation of this is to be found in the data shown in Table V, giving the field and laboratory zinc values along line 1600 E described elsewhere in this journal (5). The line along which the samples were collected crosses an area of high zinc soils as determined by the field test. The laboratory analyses confirm the field test very closely, showing the same sharp rise and fall in zinc content of the soil as obtained by the field test.

CONCLUSION.

The field method described for the estimation of total zinc content of soils is sufficiently reliable for use in geochemical prospecting provided an adequate number of soil samples are examined. Single determinations can be misleading and should never be used to formulate any conclusion. In the test locality in eastern Tennessee, the method was used effectively to locate and define areas of soil containing abnormally high zinc concentrations.

ACKNOWLEDGMENTS.

The authors are indebted to Miss Laura Reichen of the U. S. Geological Survey for laboratory analyses and many helpful suggestions, and to C. W. Whittaker of the Bureau of Plant Industry, Department of Agriculture, for help with statistical analysis of Table III.

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BIBLIOGRAPHY.

1. Axelrod, J. M., A field test for vanadium: Coptributions to geochemistry 1942–45, U. S. Geol. Survey Bull. 950, pp. 19–23, 1946.
2. Boggs, H. M., and Alben, A. O., Determination of zinc in soils: Ind. and Eng. Chemistry, Anal. ed., vol. 8, pp. 97–99, 1936.
3. Brownlee, K. A., Industrial Experimentation, 151 pp., Brooklyn, N. Y., 1947.
4. Fischer, H., and Leopoldi, G., Nachweis und Bestimmung kleiner Zinkmengen mit Dithizon: Zeitsch. anal. Chemie, vol. 107, pp. 241–269, 1936.
5. Hawkes, H. E., and Lakin, H. W., Vestigial zinc in surface residuum associated with primary zinc ore in East Tennessee: ECON. GEOL., vol. 44, pp. 286–295, 1949.
6. Hillebrand, W. F., and Lundell, G. E. F., Applied inorganic analysis, 929 pp., New York and London, 1929.
7. Holmes, R. S., Copper and zinc contents of certain United States soils: Soil Sci., vol. 56, pp. 359–370, 1943.
8. Holmes, R. S., Determination of total copper, zinc, cobalt, and lead in soils and soil solutions: Soil Sci., vol. 59, pp. 77–84, 1945.
9. Robinson, W. O., Method and procedure of soil analysis used in the Division of Soil Chemistry and Physics: U. S. Dept. Agr. Circ. 139, 21 pp., 1939.
10. Sandell, E. B., Determination of copper, zinc and lead in silicate rocks: Ind. and Eng. Chemistry, Anal. ed., vol. 9, pp. 464–469, 1937.
11. Sandell, E. B., Colorimetric Determination of Traces of Metals, 487 pp., New York, 1944.
12. Stiles, Walter, Trace Elements in Plants and Animals, 189 pp., Cambridge and New York, 1946.

PEGMATITES OF MONTANA.[1]

E. WM. HEINRICH.

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ABSTRACT.

Montana pegmatites are of three main age groups: pre-Beltian, both metamorphosed and unmetamorphosed types; Laramide, associated with the Boulder batholith; and Tertiary, related to scattered alkalic stocks and

[1] Published by permission of the Director, Montana Bureau of Mines and Geology.

small intrusives. Deposits of sillimanite, kyanite, corundum, mica, fergusonite, and chromite occur with pre-Beltian pegmatites. Laramide pegmatites contain graphite, mica, feldspar. gem amethyst, and rose quartz. Syenitic Tertiary pegmatites are characterized by numerous unusual minerals and by associated vermiculite deposits.

INTRODUCTION.

THE summers of 1947 and 1948 were spent in the field in southwestern Montana in a reconnaissance examination of the chief pegmatite areas of the state. Visits also were made to the Bearpaw Mountains and to Libby. Many of the important pegmatite deposits have been mapped in detail, and a general picture of the geology of the pegmatites has been obtained. Some of the potential pegmatite areas are still known only imperfectly, so it is possible that entire pegmatite districts as well as large individual deposits remain to be discovered. The writer believes that the pegmatites he examined are a representative fraction.

The project was suggested by Dr. Francis A. Thomson, Director of the Montana Bureau of Mines and Geology, to whom the writer is indebted for continuous active encouragement. Special thanks are due Dr. E. S. Perry, Chief Geologist of the Montana Bureau of Mines and Geology, not only for much detailed assistance in locating deposits, but also for information about several deposits that could not be visited and for a critical reading of the manuscript. In addition, most of the work on the Crystal Graphite deposit was done jointly with Dr. Perry. Dr. William Pecora of the U. S. Geological Survey graciously gave permission to publish a preview of the geology of the vermiculite deposits of the Bearpaw Mountains which he has studied in detail. Mine and prospect owners invariably gave generously of their time in guiding the writer and supplying data on history of operations. The cost of a number of polished sections of ore minerals from the Bearpaw pegmatites was defrayed by a grant from the Rackham Research Fund of the University of Michigan. This report includes a general summary of the geology and mineralogy of Montana pegmatites and brief descriptions of a few selected examples.

PREVIOUS WORK.

No general summary of the geology of Montana pegmatites has been published, but the literature contains numerous scattered references to them. As early as 1881 good quality mica is said to have been obtained from the Little Belt Mountains, near Barker in Cascade County,[2] and shortly thereafter mica sheets 8¼ × 18¾ inches reportedly were secured from a prospect 8 miles southeast of Dillon.[3] These are the only Montana occurrences recorded by Sterrett (42)[4] in his survey of the mica resources of the United States. Barrell (1) noted pegmatites in the Marysville district and described examples from the Drumlommon mine. Occurrences near Haystack Stock, Park County, were mentioned by Emmons (5). Pegmatites associated with ap-

[2] Eng. and Min. Jour., vol. 32, p. 272, 1881.
[3] Eng. and Min. Jour., vol. 47, p. 573, 1889; vol. 48, p. 230, 1889.
[4] Numbers in parentheses refer to Bibliography at end of paper.

lites in the Butte district have been recorded by Weed (46). Winchell (49) referred briefly to pegmatites in several districts in the Dillon quadrangle and adjacent areas.

The Libby vermiculite deposits were studied as early as 1911 and described first by Pardee and Larsen (29) in 1928. Landes (19) summarizes the knowledge on Montana pegmatites as follows: "Associated with the intrusive rocks in the western part of the state. Types of pegmatites: Granite (simple) and basic."

Quartz-feldspar pegmatites in association with the southern part of the Boulder batholith were examined by Sahinen (39). Similar pegmatites in the Tobacco Root Mountains had been previously described by Tansley, Schafer, and Hart (45). Pecora (30) studied the nepheline syenite pegmatites in the Bearpaw Mountains.

Rostad (38), Jovik (15), Kujawa (18), and Nordstrom (26), students at the Montana School of Mines, have prepared theses on Montana pegmatites. Drs. Perry and Cooke of the Montana Bureau of Mines and Geology noted occurrences of columbium and cerium minerals (3) and prospected for beryl (33). The U. S. Bureau of Mines explored corundum-bearing syenite pegmatites in Madison and Gallatin Counties from 1943 to 1945. The U. S. Geological Survey has examined several mica-bearing pegmatites (43).

DISTRIBUTION.

The most important known pegmatite areas are in the southwestern part of the state. By far the greatest number of pegmatite districts are underlain by metamorphic rocks of either Archeozoic or early(?) Proterozoic age, *i.e.*, rocks of the Pony or the Cherry Creek Series. Pegmatites occur less commonly in rocks of late Proterozoic age, the Belt Series. In the outer parts of the Boulder batholith small pegmatites are not uncommon, but they become less abundant toward the central parts. The writer has not observed pegmatites in the Paleozoic formations of Montana, but there remains the possibility that they were intruded into these rocks. Only recently it has been suggested that important areas of Paleozoic rocks were transformed by regional metamorphism in Laramide time (37). Laramide pegmatites might occur in such rocks. Two smaller pegmatite areas, in the north-central and northwestern parts of the state, are centered, respectively, around the Bearpaw Mountains and the town of Libby.

AGE.

The pegmatites that cut the rocks of the Boulder batholith are clearly Laramide in age, but these are relatively scarce. The most abundant group consists of unmetamorphosed pegmatites that occur in blocks of pre-Beltian rocks grouped around the margins of the batholith. It might at first be supposed that all these are genetically related to the batholith. Factors against this hypothesis include the occurrence of boulders, as much as one foot across, in a Belt conglomerate in the canyon of the Jefferson River along U. S. Highway 105, just east of La Hood Park. This unmetamorphosed pegmatite con-

tains coarsely crystalline quartz and red microcline. Second, the Sappington pegmatites are doubtless Precambrian and probably pre-Beltian in age. Third, there occur in the Cherry Creek Series aluminous pegmatites whose compositions prevent their being offsprings of the generally granodioritic Boulder batholith magma.

If, on the other hand, it is postulated that all the pegmatites in pre-Beltian rocks are pre-Beltian in age, it becomes necessary to search for a large parent intrusive of similar age. Many of the widely distributed pegmatites in pre-Beltian rocks are unmetamorphosed, and many are quartz-monzonitic in composition. One should, therefore, expect to find a large mass or at least several stocks of *unmetamorphosed* Precambrian quartz monzonite or granite. A large body of Precambrian granite has recently been recognized (9), but it is markedly metamorphosed, and is undoubtedly the parent rock of the metapegmatites in the Cherry Creek and Pony Series. Therefore, if the unmetamorphosed pegmatites are classed as of pre-Beltian age, they must be related genetically to some large nonfoliated Precambrian intrusive mass that underlies southwestern Montana and as yet is nowhere exposed—an unlikely suggestion.

Although it may be difficult to assign an individual pegmatite to a particular age group with absolute certainty, the writer has referred most of the unmetamorphosed, granitic to quartz-monzonitic pegmatites in pre-Beltian rocks to the Laramide group, even though they may be many miles from known outcrops of Laramide igneous rocks. Thus the following age groups of Montana pegmatites can be recognized:

1. Pegmatites of pre-Beltian age.
   a. Strongly metamorphosed pegmatites in Pony and Cherry Creek Series.
   b. Unmetamorphosed pegmatites in Cherry Creek rocks.
      (1) Granitic.
      (2) Aluminous.
      (3) Ultramafic.
2. Pegmatites of Laramide age.
   a. Pegmatites within the Boulder Batholith (marginal pegmatites).
   b. Pegmatites around the batholith in metamorphosed rocks, chiefly of Precambrian age (exterior pegmatites).
   c. Other pegmatites.
3. Pegmatites of Tertiary age.

PEGMATITES OF PRE-BELTIAN AGE.

Metamorphosed Pegmatites.

Locally in the rocks of the Pony and Cherry Creek Series there occur light-colored tabular masses and elongated lenses that consist essentially of quartz, microcline, and garnet. They are parallel with the foliation and layering and generally can be traced for only relatively short distances. Some are 20 to 50 feet wide and a few are 200 to 300 feet long. A strongly gneissic, medium-grained texture with most of the quartz in small parallel spindles is characteristic. Accessory minerals are oligoclase, sillimanite, biotite, magnetite, apatite, and zircon. These bodies represent pegmatite sills granulated

and recrystallized during a post-Cherry Creek and pre-Beltian period of metamorphism. This type of pegmatite occurs in large numbers in the pre-Beltian rocks east of Dillon in Beaverhead and Madison Counties. Here they were intruded into Cherry Creek rocks along the western margin of the Blacktail granite gneiss batholith of late pre-Beltian age (9). Very few of the meta-pegmatites occur within the granite gneiss itself, but they become increasingly abundant in the meta-sediments toward the batholith contact. Excellent examples are exposed near the Crystal Graphite mine and at the head of Timber Gulch (Fig. 1a) where they form conspicuous outcrops.

FIG. 1a (left). Metamorphosed pre-Beltian pegmatite in Cherry Creek marble. Head of Timber Gulch, southeast of Dillon, Montana. Bold outcrops characterize this resistant rock type. Note man in foreground for scale.

FIG. 1b (right). Minutely injected biotite schist containing sillimanite. Pegmatite at top of outcrop also contains sillimanite and has produced massive sillimanite rock along the lower contact. Proffitt Gulch, southeast of Dillon, Montana.

Microscopically the foliated texture appears more pronounced, with almost all of the quartz segregated into fine-grained lenses, ½ inch or less in length, that are set in a foliated microcline-rich matrix, also containing small amounts of oligoclase, apatite, magnetite, zircon, pennine, sillimanite, muscovite, garnet, and limonite (Fig. 4a). Pennine with secondary dusty magnetite appears to have formed at the expense of biotite or garnet. Muscovite is late and replaces chiefly feldspar. Rather coarse sillimanite needles occur in small groups almost invariably associated with the quartz lenses. Very little sillimanite was observed in microcline. The degree of crushing and recrystallization varies somewhat from place to place, but all the pegmatites are gneissic and none are zoned.

In the Jardine District in Park County, Seager (40) has described somewhat less metamorphosed pegmatites and aplites of pre-Beltian age that contain orthoclase, quartz, oligoclase, tourmaline, muscovite, apatite, garnet, andalusite, and sillimanite. The texture of the pegmatites "is distinctly gneissic with good alignment of muscovite. . . . Some of the sills have a medial zone of glassy quartz with more or less gradational boundaries and with feld-

spathic border zones." These intrusives are genetically associated with a stock of slightly metamorphosed pre-Beltian granite.

Unmetamorphosed Pegmatites.

Granitic.—The Sappington pegmatites, which are about 3 miles south-southeast of the Sappington railroad station and approximately 1 mile east of Montana Highway 1, occur in the northeastern corner of Madison County in pre-Beltian rocks near their contact with the Cambrian Flathead formation.

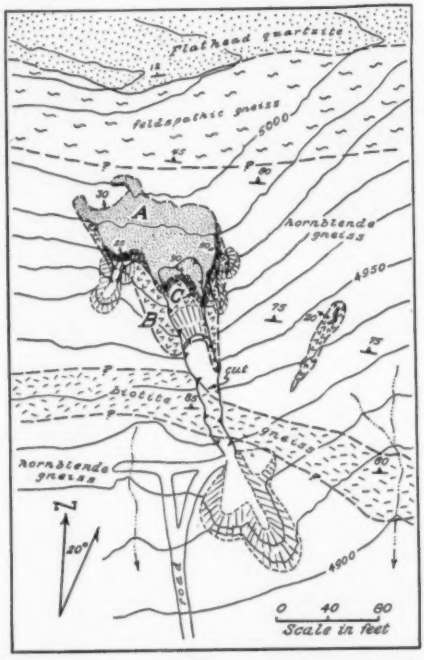

FIG. 2. Map of westernmost Sappington pegmatite, Madison County, Montana. Note the fergusonite-bearing, plagioclase-muscovite unit (C) sandwiched between the massive white to rose quartz core (A) along the hanging-wall side of the body and the medium-grained microcline-quartz zone (B) along the footwall half.

Three major and 7 minor pegmatites crop out in an area 1000 × 350 feet. Only the westernmost pegmatite (the largest) has been mined (Fig. 2). The deposits have been described briefly by Jovik (15) and by Cooke and Perry (3).

The country rock consists of interlayered hornblende gneiss (dominant), a layer of biotite gneiss, and a poorly defined horizon of feldspar-rich gneiss

near the Flathead contact. The metamorphic foliation strikes east-west and dips 45–75° N. The larger eastern pegmatites are conformable in a general way to the metamorphic structure, but most of the other deposits transect the foliation at nearly right angles. Within the basal Flathead conglomerate occur sub-angular pieces of white quartz, as much as 6 inches across, that resemble closely the quartz of the pegmatite cores.

The westernmost pegmatite, an irregular pod-like body that strikes N. 75° E. and dips 30–50° NW., is 100 feet long and 110 feet in maximum thickness (Fig. 2). The larger part consists of a core of massive white to locally deep rose quartz, as much as 70 feet thick, which lies along the hanging-wall side and is separated from the gneiss by a very thin zone of feldspathic pegmatite. Regularly spaced fractures in the quartz strike east of north and dip 75° SE. The footwall contact of the core dips moderately northwest.

The wall zone is strongly developed on the footwall side, where it may be as much as 35 feet thick. It consists chiefly of microcline and quartz, with minor muscovite, sodic plagioclase, magnetite, and black tourmaline. Quartz and microcline are commonly subgraphically intergrown; locally 3-inch masses of quartz-free microcline occur.

Near the walls another local rock type consists of a fine-grained, vuggy aggregate of quartz, light colored microcline, and parallel green muscovite scales. Small muscovite crystals occur in the vugs. In the main cut an apophyse from the footwall is made up of a highly vesicular mass of interlocking dark green muscovite crystals with interstitial and bordering films of plagioclase and quartz and irregular, scattered remnants of microcline. Some of the cavities contain muscovite crystals as much as ½-inch across; others have linings of fine-grained plagioclase. The rock results from replacement of wall zone pegmatite localized along the contact.

Lying directly below the core is a 3- to 6-foot unit rich in plagioclase and coarse muscovite. Much of the mica is arranged in semi-rosettes of radiating blades or in comb-structure blades normal to low-angle fractures. Some muscovite blades project upward into the core, and the contact with lower wall zone rock is gradational. In this intermediate rock wall zone microcline has been replaced preferentially by veinlets and patches of fine-grained, bright green muscovite, resulting in an aggregate of rounded quartz anhedra and corroded microcline crystals in a network of mica.

Radioactive fergusonite occurs in the unit in irregular pods and blebs as much as 3 inches long surrounded by dark red microcline and albite, which it has partly replaced. In many specimens it clearly follows the feldspar cleavage. Muscovite and secondary calcite are common associates. The mineral is dark brown to resin brown in hand specimen, but under the microscope a small amount of bright yellow material (microlite?) can be seen in minute patches. In minute fragments the material is yellow to pale brown in color. It is isotropic with an index of refraction from 1.83–1.84. The composition is apparently near the fergusonite end of the fergusonite-formanite series, for more columbium is present than tantalum. A spectographic analysis has been made by Cooke and Perry (3). Although the index of refrac-

tion and specific gravity (3.95) are too low for fergusonite, X-ray powder photographs have established the identity of the considerably altered mineral.

Mica from the main pegmatite is pale silvery green in color and contains only scattered spots of magnetite. A-structure and cracks are strongly developed; herringbone and wedge structure are moderately developed. Books as much as 8 inches across were observed; five-inch books are common.

This pegmatite and others nearby are pre-Flathead and probably pre-Beltian in age. About 10 airline miles northwest of Sappington a Belt conglomerate contains boulders of unmetamorphosed pegmatite, which may have been derived from the erosion of pegmatites similar to those near Sappington. These pegmatites probably were formed during a restricted intrusive period after the final deformation of the Cherry Creek rocks and before the deposition of the Belt.

Fergusonite also has been found in a placer near Laurin, presumably derived from pegmatites. It has been suggested by Perry and Cooke (33) that fergusonite may be diagnostic of unmetamorphosed Precambrian pegmatites and that allanite characterizes pegmatites of Laramide age. This may well be true, but the number of occurrences of these minerals is so small that they can hardly be used as age criteria. Moreover, allanite is apparently confined to Laramide pegmatites in quartz monzonite and granodiorite,[5] which offer no difficulty as to their age. Its presence, therefore, neither helps nor hinders age determination; nor is its absence diagnostic.

If the few Sappington deposits examined are representative unmetamorphosed pre-Beltian pegmatites, the following characteristics may help to distinguish them from unmetamorphosed Laramide pegmatites: The bulk composition of the Precambrian pegmatites is granitic, whereas many of the Laramide pegmatites contain important amounts of primary sodic plagioclase, and in some this mineral exceeds microcline; biotite and tourmaline appear more abundantly in Laramide pegmatites; and pyrite, epidote, and chlorite appear to be confined to those of Laramide age.

Aluminous Group 1. Bozeman Corundum Pegmatites.—Three groups of corundum deposits are known in the vicinity of Bozeman. The Bozeman deposit is 12 miles S. 70° W. of Bozeman in Gallatin County on a flat, northeast-trending nose that is bounded on the northeast and southeast by gentle valleys (28). The Gallatin deposit (or Montana or Fuller deposit) lies 5 miles S. 35° W. of the Bozeman deposit and 17 miles S. 60° W. of Bozeman in Gallatin County on Elk Creek (27). The Bear Trap deposit is 9 miles S. 60° E. of Norris in Madison County, on the north side and near the headwaters of Bear Trap Creek (11).

All three deposits occur in the Cherry Creek Series. At the Bozeman deposit quartzite, hornblende-garnet gneiss, biotite-garnet schist, and biotite schist are exposed. Quartzite, hornblende schist, and hornblende-biotite gneiss are interlayered at the Gallatin deposit. In addition biotite-muscovite schist and pyroxene-garnet gneiss occur near the Bear Trap workings. Some of the quartzites at the Bozeman mine are rose colored; others at the Bear

[5] For example, the small pegmatites near Janney, south of Butte, contain quartz, microcline, sodic plagioclase, biotite, epidote, schorl, garnet, pyrite, chlorite, and allanite.

Trap deposit are bright green and contain pale green muscovite. At the Bozeman mine the foliation strikes a few degrees west of north and dips 20–50° N. At the other two mines it strikes N. 60–75° E. and dips moderately to steeply northeast.

The geology of the three deposits is very similar. Corundum occurs in lenses and tabular bodies of syenite pegmatite intruded along the foliation and between layers of the metamorphic rocks. Individual bodies may be as much as 1,000 feet long; the maximum thickness is about 5 feet. However, many of the sills are only a few score feet long and 1 to 2 feet thick. They tend to occur in swarms of 10 to 15.

The texture is medium- to coarse-grained and generally somewhat foliated due to biotite orientation; the main mineral constituents are abundant microcline microperthite, some orthoclase, corundum, plagioclase (Ab 90), and

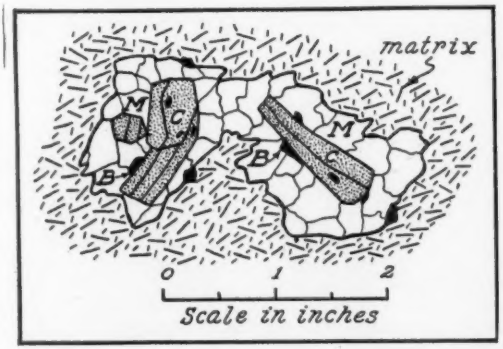

FIG. 3. Corundum crystals (C) with baddeleyite (B) in shells of microcline (M) set in a matrix of finer-grained microcline, oligoclase, biotite, and minor sillimanite. From syenite pegmatites at the Gallatin deposit, southwest of Bozeman, Montana.

biotite. Plagioclase is subordinate to potash feldspar. The accessory minerals are black tourmaline, apatite, zircon, magnetite, kyanite, quartz, and a mineral that resembles rutile but has been identified as baddeleyite by Rogers (35). In some of the pegmatites sillimanite and muscovite become very abundant. The blue-gray, opaque corundum occurs in an unusual, characteristic fashion. It forms euhedral, hexagonal prisms as much as eight inches long, which commonly include grains of baddeleyite or have grains of baddeleyite along their margins. The prisms are almost invariably set in a shell of microcline whose thickness is proportional, in a rough way, to the size of the prism (Fig. 3). The crystals generally lie across the foliation; a few are curved.

The microscope reveals that the smaller corundum crystals commonly are skeletal with numerous inclusions of baddeleyite and perthitic microcline and

that the shell consists almost exclusively of perthitic microcline. Corundum hardly ever is in contact with biotite, quartz, or plagioclase.

Many of the sills contain abundant sillimanite and muscovite, which are clearly later than the other minerals and have been developed at their expense. The conspicuous replacement by muscovite begins along the contacts between corundum crystals and their microcline shells and engulfs first the shell; then the rest of the potash feldspar in the matrix is replaced selectively (Fig. 4b).

The more general replacement by sillimanite produces a strong schistose appearance in the rock. All gradations exist from normal syenite pegmatite without muscovite or sillimanite through varieties in which sillimanite is a subordinate constituent of the matrix and muscovite rims the corundum, to those that consist essentially of coarse, radiating needles of sillimanite and plates of muscovite with corroded relicts of corundum and very minor residual biotite, sodic plagioclase, baddeleyite, and zircon.

FIG. 4a (left). Metamorphosed granite pegmatite of pre-Beltian age, near Timber Gulch, southeast of Dillon, Montana. Note the quartz (Q) in spindles in matrix of recrystallized microcline and muscovite (M). Sillimanite (S) has been formed near and in a quartz spindle. Garnet (G) is veined by chlorite (C). × 16.

FIG. 4b (right). Muscovite (Mu) replacing microcline (Mi) along contacts with corundum (C). Other minerals are plagioclase (P) and baddeleyite (B). From syenite pegmatite at the Gallatin deposit, southwest of Bozeman, Montana. × 26.

Streaks and tabular masses of sillimanite are concentrated locally along pegmatite contacts. Where pegmatites have been intruded into hornblende-rich rocks, thin seams of vermiculite sheath the walls. Some of the sills appear to have been localized along contacts between quartzite and hornblende gneiss.

With the syenitic pegmatites a few granitic pegmatites are closely associated. They contain quartz, microcline, sodic plagioclase, and green muscovite as the main constituents and as accessories, biotite, garnet, schorl, and blue apatite; small vugs contain muscovite crystals. In the Elk adit at the

Gallatin deposit a two-foot pegmatite grades from syenitic (with corundum and sillimanite) to granitic and back to syenitic within a strike length of 80 feet.

Similar corundum-bearing rocks have been described by Holland (10) from the Paparapatti area of the Salem District of Madras. The sill-like lenses, which occur in charnockite gneiss, contain perthitic orthoclase, corundum, sillimanite (often in considerable amounts), rutile, black and green spinel, and biotite, which is especially abundant in the outer parts of the lenses. Holland (10) states, "Each (corundum) crystal is surrounded by a shell of purer orthoclase, generally flesh-coloured, but sometimes white, having a thickness of from one-fourth to one-eighth inch. . . . Microscopic examination shows that this shell differs from the remainder of the matrix in the absence of minute corundums, sillimanite and most of the accessory minerals."

Corundum-bearing syenites are also known from the Ural Mountains (25) and from the eastern part of Ontario (24), as well as from Montana. These occurrences are similar in their general geology, but only the India and Montana rocks contain sillimanite. The Ural material apparently does not have corundum set in ovoids of potash feldspar.[6] All contain potash-feldspar as the chief mineral and varying amounts of biotite. This type of corundum-bearing pegmatite appears to be unrelated geologically to the so-called "desilicated pegmatites"—albite and plumasite, in which the chief feldspar is sodic plagioclase and which are commonly intrusive into ultramafic rocks.

The large euhedral corundum crystals were the first to form, precipitated from a magma with an excess of aluminum. Within the immediate vicinity of these phenocrysts the concentration of aluminum was therefore reduced, and biotite could not crystallize. Thus the ovoids consist only of potash feldspar. Minute skeletal corundum crystals continued to develop throughout the period of matrix crystallization and do not have the haloes. Post-crystallization solutions rich in aluminum locally converted microcline to muscovite and biotite and microcline to sillimanite.

Aluminous Group 2. Ennis Kyanite Pegmatites.—The kyanite deposits 13 miles S. 13° W. of Ennis in Madison County have been described (8, 26). Rocks of the Cherry Creek Series underlie the area, with dolomitic marble, biotite gneiss, biotite-garnet gneiss, and hornblende gneiss and schist as the dominant types near the deposits. Immediately around the pegmatites kyanite and sillimanite become important rock constituents.

The quartzose kyanite-bearing pegmatites occur only in mica-garnet gneiss and are especially abundant around the nose of a marble fold, in a fracture zone probably developed as a result of the folding. Some of the lense-like bodies cut across the contorted foliation; others follow the foliation. They range in length from a few feet to 150 feet and in width from several inches to 30 feet. Most contain a core of massive white quartz (as much as 75% of the outcrop), surrounded by a thin outer shell of quartz-feldspar pegmatite. Others are quartz-rich and have minor feldspar.

[6] Miller (24) in Fig. 2, following p. 216, shows corundum in a shell of feldspar, free of dark colored minerals.

Other minerals are white to pink microcline, white andesine (Ab 60), muscovite, kyanite, sillimanite, schorl, biotite, garnet, apatite, graphite, and sericite. Schorl, several inches long, is concentrated around the margins of kyanite blades. Olive yellow, waxy, massive sericite occurs abundantly as irregular masses replacing feldspar.

The blue kyanite is coarsely-bladed, six inches or less in length, but averages about an inch. Silvery muscovite replaces it along the cleavage. Kyanite occurs both in the core and in the wall zone, where it is more abundant, although the largest crystals are in quartz. In a few deposits it forms a narrow selvage along the walls. The mineral is generally unoriented.

Most of the small pods of white fibrous sillimanite replace kyanite and are closely associated with the massive sericite. The relation between the aluminum silicates can also be seen in thin section where kyanite blades are corroded and veined by later sillimanite. In one pegmatite a two-inch vein of quartz and cross-fiber sillimanite cuts across the 1½-foot sill at right angles from wall to wall. Graphite is widespread in very minute flakes scattered through feldspar, kyanite, and sillimanite. Most of the gneiss contains little or no kyanite, but surrounding the pegmatites an aureole of kyanite-rich rock has been developed. These aureoles, 10 to 25 feet wide, contain coarse kyanite blades that lie across the foliation. Farther from the pegmatite, the size and amount of kyanite decreases, and the gneiss becomes kyanite-free. Kyanite and sillimanite are both late minerals in the pegmatites. The development of kyanite in the aureoles does not represent mere crystallization of elements present in the gneiss at the time of intrusion, but required the addition of aluminum by pegmatitic solutions.

It can be argued that the fluids became aluminum-rich through the solution of aluminous material from lower horizons. Locally, at least, there should be exposed rocks robbed of their aluminous constituents. No such rocks are present. The alternative hypothesis postulates that the original solutions were unusually rich in aluminum and that the kyanite and sillimanite are of magmatic origin. Stuckey (44) has advocated a similar pegmatitic origin for North Carolina kyanite. The hypothesis of magmatic segregation advanced by Read (34) and by Spaenhauer (41) for kyanite-quartz veins on the island of Unst, Shetland Islands, and at Silvretta, Switzerland is inadequate to explain all the facts of the Montana occurrences. Even less plausible is the hypothesis of Dunn (4), who stated that the massive aluminum silicate bodies in India were formed by the regional metamorphism of sedimentary lenses of high-grade clay.

It is significant that another type of pegmatite, granitic in composition and of possible Laramide age, has also been intruded into the gneiss without the production of kyanite. Thus it seems that the formation of the kyanite is dependent neither on the type of immediate wall rock nor on the type of rock through which the pegmatites passed at depth, but is related to the nature and composition of the pegmatitic magma.

Aluminous Group 3. Dillon Sillimanite Pegmatites.—In the Cherry Creek Series 13 miles east and southeast of Dillon in Beaverhead County occur several groups of pegmatites that contain sillimanite and with which silliman-

ite rocks are associated. The country rocks are marble, hornblende gneiss, biotite gneiss, and biotite schist. The pegmatites, which contain quartz, potash feldspar, plagioclase, sillimanite, and muscovite, have been intruded along the foliation of coarse-grained biotite schist. Only where the schist has been intensely and minutely injected by small closely spaced stringers of quartzose, sillimanite-bearing pegmatite, does it contain abundant ¼- to 1-inch "knots" and "eyes" of finely felted sillimanite (Fig. 1b). Along the walls of larger pegmatites, which may be 100 feet long and 10 feet thick, pods of massive sillimanite rock, as much as 2 feet long, have been formed. This rock is dense and very tough, consisting chiefly of minute interlocking fibers of white to pale green sillimanite with scattered relict flakes of biotite. A complete gradation exists from biotite schist without sillimanite, through biotite schists with lenticles of sillimante associated with intense small-scale pegmatitic injection, to rocks that contain 90% sillimanite and occur along the contacts of the larger pegmatite sills. These also carry variable quantities of sillimanite along fractures. There has clearly been an addition of aluminum to the biotite schists. That the sillimanite rock is not a product of regional metamorphism is shown by its distribution: it does not occur in well-defined layers as do the other metamorphic rock types, and the associated rocks are medium grade metamorphics. It should be noted that, as in the Ennis kyanite deposits, younger muscovite pegmatites in the biotite schists are not accompanied by sillimanite. Thus it appears that here, too, the development of aluminum silicate was a function of the type of pegmatitic magma and not of the nature of the country rock.

Ultramafic.—The Stillwater complex has been intruded into metamorphic pre-Beltian rocks and is most probably also of pre-Beltian age. Chromite ore occurs in the Stillwater complex with mafic pegmatites that contain olivine, orthorhombic pyroxene, plagioclase, diopside, and chromite. According to Peoples and Howland (32), "An almost constant associate of the chromite is a very coarse-grained or pegmatitic harzburgite with interstitial feldspar and disseminated chromite grains. This rock may occur above, below, or within the chromite-bearing layer."

PEGMATITES OF LARAMIDE AGE.

General.

The pegmatites of Laramide age are those genetically associated with the Boulder batholith. They fall into two groups: those that occur within the batholith itself near its margins (marginal pegmatites) and those that occur in metamorphic rocks around the batholith or its cupolas (exterior pegmatites). Each group has its own structural and mineralogical characteristics.

The marginal pegmatites are, with few exceptions, closely associated with generally larger bodies of aplite within which they may occur as local segregations or tabular masses. Although aplite dikes are uncommon outside of the batholith, aplitic intrusives occur with exterior pegmatites at the Birds Nest graphite mine and the Timber Gulch talc deposit near Dillon.

In the interior type primary vugs containing clear to smoky quartz crystals and microcline crystals, are common.[7] Quartz and microcline are generally intergrown in a medium-grained granitoid aggregate that grades into micropegmatite. Variable amounts of oligoclase are present, and later albite crystals also occur perched on quartz crystals. Biotite is much more common than muscovite. Schorl is abundant; rare accessory minerals are garnet, apatite, magnetite, and hornblende. Particularly characteristic seem to be scattered pyrite cubes, and locally pyrrhotite, chalcopyrite, and molybdenite occur. In addition to the sulfides, other diagnostic minerals are sphene, allanite, chlorite, epidote, and clinozoisite, the last in the pegmatites of the 19-Mile Picnic Grounds, near Butte. Late amethyst characterizes the hydrothermal mineralization in the Pohndorf pegmatite.

With a few exceptions the interior pegmatites are poorly differentiated, but small quartz cores occur in some. Most of the bodies are only several feet thick and several score feet long; a few are ten to fifteen feet wide and about a hundred feet long. They have had no discernible effect upon their wall rocks, which are granodiorite, quartz monzonite, or aplite. Many of those in aplite do not appear to have been injected, but were accumulated as volatile-rich residua.

The exterior pegmatites are for the most part lenses or tabular sills of moderate size. They show variable development of zoning, and often several units are well developed. Border zones are rare, but wall zones, intermediate zones, and cores are recorded. Cores are quartzose, often consisting of rose quartz (Ramshorn Creek, near Sheridan). Intermediate zones are usually rudimentary, occurring as clusters of large microcline crystals around the margin of the quartz core. However, many pegmatites in this group have no zonal arrangement and consist entirely of a rather uniform, coarse-grained quartz-microcline aggregate with scattered accessory minerals. A primary foliation was observed in the wall zone of one pegmatite, around an undisturbed feldspathic core.

The pegmatites are granitic, quartz monzonitic, or granodioritic in composition. The zoned bodies contain a higher proportion of oligoclase. The wall zones may contain chiefly oligoclase and only very minor microcline, which is concentrated in intermediate zones. The unzoned pegmatites contain less plagioclase. It has been suggested that molybdenite is a characteristic accessory mineral in the granitic type, whereas pyrite, chalcopyrite, and pyrrhotite characterize the quartz-monzonitic deposits.[8]

In two deposits microcline occurs as amazonstone (well developed in the Lost Creek Falls pegmatite north of Anaconda). Graphic granite is not uncommon in some of the unzoned pegmatites, and graphic quartz-oligoclase rock occurs in some of the zoned deposits. Graphic intergrowths of quartz-tourmaline and quartz-garnet also were noted. Large crystals of schorl are common. Sahinen (39) describes a pegmatite from the southwestern part

[7] Maguire, (23) p. 255, states, "There is much of the crystallized quartz found in the intermountain country that shows inclusions of black, brown, pink, and green tourmaline; notably near Boulder, Jefferson County, Montana, near Highland, in the Tobacco range of mountains, Madison County; in Beaverhead County, Montana . . . ."

[8] Private Communication from Charles Meyer, Butte, Mont.

of the Vez Perce Basin that contains abundant quartz, black tourmaline, and some copper sulfides. The abundance of tourmaline in these pegmatites also indicates that they were derived from the Boulder batholith magma. The concentration of boron in emanations from this magma has been noted by Knopf (16). Numerous quartz-fibrous tourmaline veins also occur in the Boulder batholith near the Butte reservoir.

Garnet is not an uncommon accessory mineral. Muscovite is more common and much coarser-grained than biotite. Epidote is abundant in some, as for example along the Ennis-Virginia City road, but chlorite and iron sul-

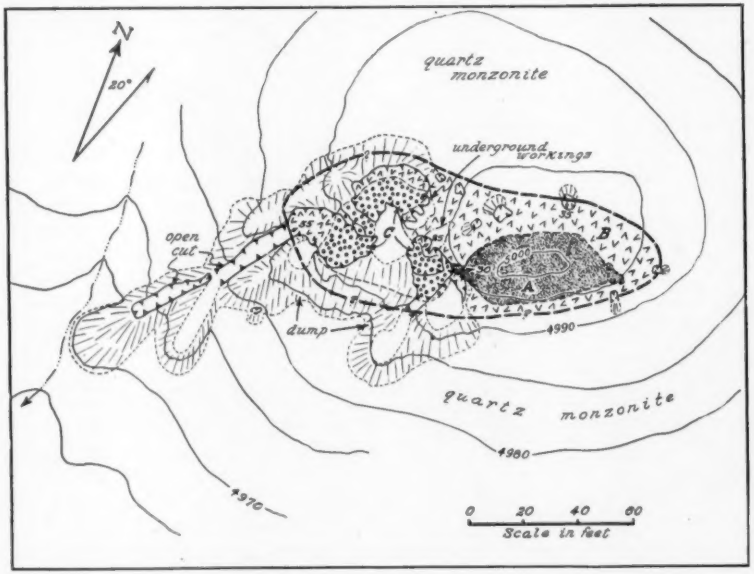

FIG. 5. Map of Pohndorf amethyst pegmatite near 19-mile picnic grounds, Jefferson County, Montana. A = quartz core, B = wall zone of medium-grained microcline-quartz pegmatite, C = vuggy microcline-quartz-amethyst pegmatite unit which dips at low angles beneath the core.

fides are found rarely. Uncommon accessory minerals are graphite, beryl, apatite, magnetite, zircon, andalusite, and fluorite.

Beryl has been identified with certainty only from the Big Chief pegmatite near Sheridan, the White Swan pegmatite on the East Fork of Granite Creek north of Virginia City, and the San Miguel pegmatites near Monarch, southeast of Great Falls. The general absence of beryl is characteristic of the exterior pegmatites, despite an early statement by Maguire (23) that "Beryl occurs in Montana . . . in considerable quantities . . . in Jefferson County." Winchell (49) noted the presence of fluorite in pegmatite in the Highland

District, south-southeast of Butte, associated with green muscovite and tourmaline.

Many pegmatites lie parallel with the metamorphic foliation; others cross it. Some have been emplaced along small faults or along contacts between two rock units (Fig. 6).

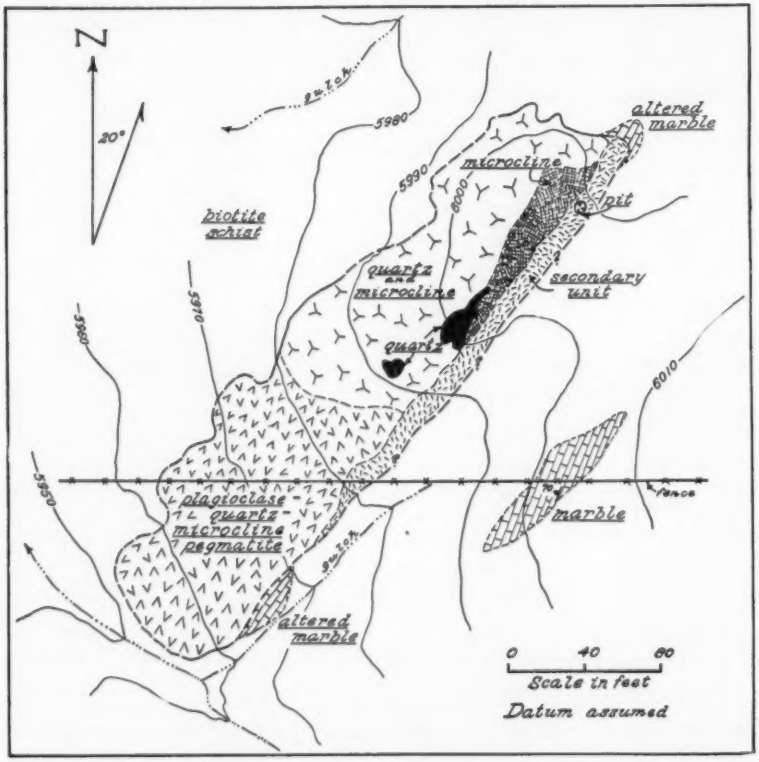

FIG. 6. Map of Stone Creek pegmatite, ½ mile south of Stone Creek, northeast of Dillon, Montana. The pegmatite is emplaced along a marble-biotite schist contact and appears to dip at a moderate angle northwest. Note the replacement unit of cleavelandite-muscovite-ilmenite rock localized along the footwall contact.

Where the pegmatites intrude marble small crystals of diopside, actinolite, and phlogopite may be developed. Locally the marble has been converted to a brown siliceous aggregate. Elsewhere masses of coarsely crystalline actinolite and "nests" of phlogopite may be present. In one example fine-grained purple cordierite was formed. In hornblende gneiss where small-scale lit-par-

lit injection has taken place, coarse-grained hybrid rocks have been formed, containing abundant hornblende, quartz, microcline, plagioclase and accessory chlorite, biotite, epidote, and magnetite. Examples were noted on State Highway 34 between Virginia City and Laurin in Madison County, near Timber Gulch on the northeast side of Blacktail Deer Creek, and near the graphite deposits on the McBride Creek-Kate Creek divide, both in Beaverhead County. The intrusion of other pegmatites into hornblende gneiss or amphibolite has produced local pods and masses of anthophyllite.

Several more mafic pegmatites may also belong to this group. Johnston (13) states, "Certain of the pegmatite dikes (around the Tobacco Root batholith), which are basic in character, have been cut by the acidic dikes." The quartz-diorite pegmatites associated with the mafic dikes on Horse Creek near Sheridan, and the hornblendite pegmatite on Mica Creek south of Gallatin Gateway are probably Laramide in age.

Marginal Pegmatites.

Timber Butte Pegmatites.—The medium- and uniform-grained quartz monzonite of Timber Butte, a conspicuous knob 2 miles south of Butte, is cut by numerous dikes of aplite-pegmatite (38, 49), whose thickness ranges from 6 inches to 3 feet. One dike was traced for 1,000 feet, but most are only a few tens of feet long. They strike generally north-south and are vertical. In some the contacts are sharp; in others, gradational. Many have a central vug; this passes into medium-grained granitoid pegmatite, then fine-grained graphic granite, and finally aplite. Quartz, microcline, plagioclase, black tourmaline, magnetite, biotite, and sphene are the constituents.

Some vugs contain quartz crystals, 1 × ½ inch, with dark smoky tips and a few microcline crystals. Anhedral interstitial tourmaline is molded between quartz and feldspar crystals. Beautiful large crystals of translucent yellow sphene have been obtained.[9] They are flattened parallel with the c-axis and twinned with {100} as the twinning plane.

Pohndorf Amethyst Pegmatite.—The Pohndorf pegmatite is 2 miles northeast of the Toll Mountain picnic grounds in southwestern Jefferson County. The deposit, a lens-shaped pegmatite in Boulder batholith quartz monzonite, is 140 feet long and as much as 55 feet wide. It trends N. 60° E. and from the internal structure appears to be of limited vertical extent. The core, which is at the northeast end (Fig. 5), is 60 × 25 feet in plan and appears to be flat-lying. It is enclosed in an outer zone of fine- to medium-grained rock that contains buff microcline, quartz, sodic plagioclase, apatite, biotite, muscovite, magnetite, and sphene. Bright green flakes of muscovite appear to be replacing feldspar; graphic granite is absent.

In three prospect pits a third rock type underlies the finer-grained pegmatite and dips eastward beneath the core. It consists of a vesicular to vuggy aggregate of microcline and quartz, much of which occurs in partly faced crystals. Crystals of microcline 1½ feet long were obtained. Both minerals have been strongly corroded, and on the corroded faces tourmaline, sericite, albite,

[9] Private Communication from Arthur Montgomery, Boston University.

and amethyst have been deposited. The microcline is deeply grooved along cleavage directions and is peripherally replaced by albite. Coatings of green sericite are common, as are patches and shells of fibrous black tourmaline.

The quartz is milky, clear, and smoky (90%). Most of the dark color is due to abundant minute fibers of black tourmaline, which also forms coatings on quartz and pseudomorphs after quartz. Many of the irregular crystals were broken fragments without crystal faces but have received faces through secondary growth. Parallel growth groups, curved faces, and broken and corroded crystals are common.

The generally small amethyst crystals are perched on the sides and tops of tourmalinated quartz. The color ranges from dark brownish purple to bright lavender, and some of the crystals were of excellent quality. In the more light-colored ones the color is darker at edges, corners, and the apex.

Most of the overgrowths on the quartz crystals are directional, *i.e.*, they occur more abundantly on several faces. Some tourmalinated crystals were corroded and replaced on three prisms; others have sericite overgrowths on only 3 or 4 prisms; perched albite and amethyst crystals are commonly confined to one or two sides.

The paragenetic sequence is:

1. Crystallization of a pegmatite magma by differentiation into wall zone (fine-grained rock), intermediate zone (coarse-grained quartz and microcline), and core (massive quartz).
2. Corrosion and solution of intermediate-zone rock by hydrothermal solutions passing along the contact with the core and formation of a vuggy aggregate of microcline crystals and anhedral quartz pieces.
3. Deposition of new quartz on the fragments. Later tourmaline began to form and was first included in the newly deposited quartz. Still later it coated and corroded both quartz and microcline. Veinlets of quartz and tourmaline formed in microcline.
4. Deposition of albite on tourmalinated quartz crystals and corroded microcline crystals; replacement of some microcline by albite.
5. Deposition of sericite on all other minerals.
6. Deposition of amethyst crystals on quartz crystals.

Lake Delmoe Pegmatites.—Allanite, which has been reported by Cooke and Perry (3) from gold placer deposits near Lake Delmoe in Jefferson County, probably was derived from small pegmatites in quartz monzonite. Typical pegmatite groups are exposed on the road south of Lake Delmoe and along its margins. The pegmatitic rock invariably is associated with aplite dikes as much as 50 feet thick, in which it occurs as small, irregularly distributed, streaks, often enclosed in fine-grained micropegmatite.

The lenses, which are generally a few feet long and less than a foot across, contain numerous small primary vugs lined with microcline crystals one inch long, smoky quartz, pyrite, and golden sphene. Interstitial minerals are bladed oligoclase and anhedral schorl. Around the vugs one inch blades of epidote and intergrown red garnet and quartz occur in quartz-microcline rock. Other accessory minerals are biotite, magnetite, and a few blades of allanite.

Exterior Pegmatites.

Montana Pegmatite.—The Montana deposits are on the upper reaches of Granite Creek on the western side of the crest of the Tobacco Root Mountains, in Madison County. The main pegmatite body, which is exposed in the walls of a cut, 25 × 18 × 15 feet, and also a few feet below the collar of a 60-foot shaft, has a maximum thickness of 15 feet, but the northeast contact is concealed. The vertical southwest contact strikes N. 70° W. In the shaft the dip is moderate southwest. The country rock is interlayered mica gneiss, garnet gneiss, and hornblende-garnet gneiss, whose foliation strikes N. 5° E. and dips 80° NW. In a bulldozer cut west of the shaft it contains 3-inch garnet metacrysts.

A 2-inch border zone is composed chiefly of 1-inch muscovite books. The wall zone, 6 inches to 2 feet thick, consists of a subgraphic intergrowth of white sodic plagioclase and quartz with subordinate microcline, sericite, and a few one-inch garnet euhedrons. The northeast part of the wall zone also contains pods of quartz-muscovite rock. The core, 10 feet thick in the northwest corner of the pit, pinches out to the southeast and contains 2-foot quartz pods alternating with masses of graphic quartz-feldspar rock, cut by thin 5-foot strips of intergrown biotite and muscovite. Books of muscovite, 10 inches long, are scattered throughout the core, and a few foot-long blocks of white microcline lie along the north side. In the shaft the pegmatite splits into three branches and is unzoned.

Dulea Pegmatite.—The Dulea pegmatite, which is 1½ miles south of the Montana mine, is an irregular dike exposed in a pit about 25 feet in diameter and 15 feet deep. It strikes N. 50° E. and the footwall contact dips 70° NW. to vertical. A 4-foot footwall apophyse trends S. 60° W. and dips 60° SE. The hanging wall, as exposed in a 70-foot bulldozer cut north of the pit, dips 80° NW. The country rock, whose foliation strikes N. 30° E., consists of hornblende gneiss, locally garnetiferous, and a layer of lustrous brown anthophyllite amphibolite at the pegmatite contact.

The core contains 3-foot quartz pods and masses of blocky microcline. The wall zone consists of coarse microcline, plagioclase, biotite, muscovite, garnet, and biotite in large cross-cutting plates and strips. Six-inch mica books occur chiefly below the core. The mineral is gray-green in color with scattered dots of iron oxide, flecks of bright green material, and some quartz inclusions. Most books are flat and hard, but reeves are well developed.

Stone Creek Pegmatite.—The Stone Creek pegmatite lies on the divide area between Stone and Carter Creeks in Madison County (Fig. 6). The deposit, which is 350 feet long and 90 feet wide, has been intruded along the contact between marble and biotite schist (on hanging wall). It strikes N. 45° E. and dips moderately northwest. Locally along the marble contact the carbonate rock has been altered to fine-grained brown chert and to actinolite schist.

The well-developed internal structure consists of the following units (Fig. 6):

1. A wall zone that occupies the southwestern half of the body and contains coarsely-twinned white plagioclase (Ab 85), quartz, subordinate white microcline, and accessory black tourmaline and muscovite. Tourmaline is locally very abundant.
2. An intermediate zone that makes up most of the northeastern part of the pegmatite. It consists of very coarse-grained microcline and quartz. The feldspar occurs in crystals 3 to 4 feet across and is of excellent quality. This zone grades into
3. A hood zone containing only very coarse, blocky microcline, which extends northeast from
4. A core of white quartz, about 35 feet long. A smaller pod lies to the southwest.
5. Along the footwall side at the marble contact is a secondary unit that represents replaced wall zone rock. The wall zone minerals are present, but coarse muscovite and tourmaline are much more abundant. In addition cleavelandite, apatite, and ilmenite are plentiful, the latter in plates several inches long. A fist-sized mass of fine-grained lepidolite also was noted.

Keystone Pegmatites.—The Keystone pegmatites are one mile northeast of the Keystone Talc mine on Carter Creek, in Madison County. The main dike, which is 850 feet long and 30 to 85 feet wide, strikes generally N. 70° SE. (Fig. 7). Several blunt apophyses extend from the hanging wall across marble that has been altered locally to a brown, fine-grained, silicified rock or to phlogopite-actinolite rock. Footwall marble is relatively unaltered. At the northeast end hornblende gneiss forms a metamorphosed mafic sill in marble. A small mass of a very fine-grained basalt crops out east of the dike. The marble layering strikes on the average east and dips 53–68° N. Marble blocks caught between pegmatite apophyses were rotated to a nearly north strike and a variable dip.

The well-zoned pegmatite contains:

1. A core of massive, milky quartz, the largest pod of which is 190 feet long. Three other smaller pods crop out; one occupies most of the northeastern apophyse (Fig. 7).
2. An intermediate zone of 2- to 4-foot high-quality microcline euhedrons in massive quartz.
3. A small hood of massive microcline lying above the core pod in the western part of the dike.
4. A wall zone of medium-grained microcline-quartz-sodic plagioclase rock, rather uniform in texture and composition except in the two blunt protuberances from the western part of the hanging wall, where tourmaline crystals are unusually abundant and biotite blades occur locally. Tourmaline appears to replace microcline. The localization of this late boron mineral in the two small cupolas above the main mass of pegmatite is very striking and represents the late crystallization of trapped volatile-rich material that had risen and accumulated in the rounded bulges.

Several hundred feet northeast, a group of smaller pegmatites of similar composition and structure, contain muscovite and tourmaline which are especially abundant around deep rose quartz cores.

Crystal Graphite Deposit.—The Crystal Graphite deposit lies on the ridge between Camp Creek and Axes Canyon, 11 miles southeast of Dillon. The deposit has been studied by Winchell (47, 48, 49), Bastin (2), and Hum (12).

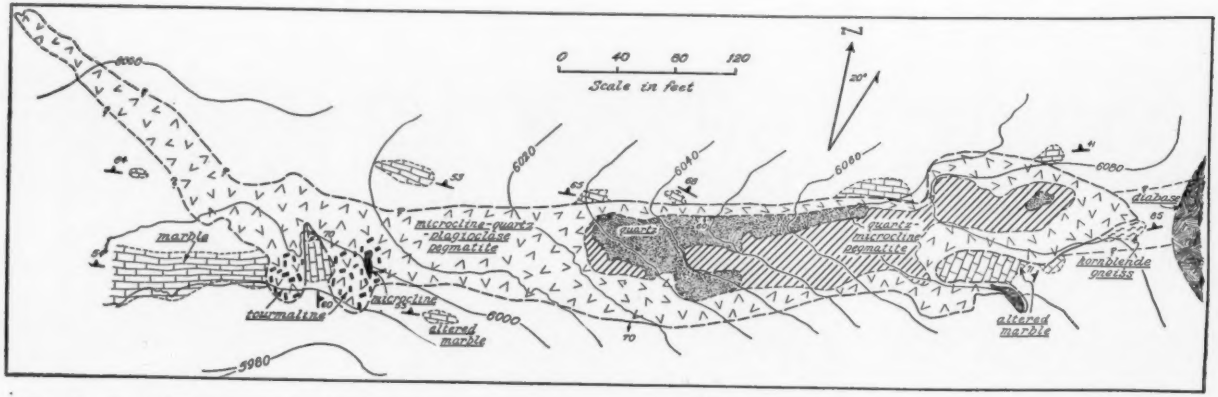

FIG. 7. Map of Keystone pegmatite, Carter Creek drainage, northeast of Dillon, Montana. Note the concentrations of tourmaline in the two upward bulges from the western part of the hanging wall.

The area is underlain by Cherry Creek rocks, whose foliation strikes N. 40–60° E. and dips 30–60° NW. The chief types are: (1) biotite and biotite-garnet gneiss locally intensely granitized with eye-shaped feldspar metacrysts, (2) hornblende, hornblende-garnet, and hornblende-augite gneiss; and (3) marble and thin layers of lime-silicate gneiss. Minor rocks are quartzite and sillimanite schist. A layer of dolomitic marble that is 150–200 feet wide, strikes N. 50° E., and dips 40–45° NW., ends in a rounded nose 400 feet northeast of the main workings. The nose appears to plunge about 40° N. 30° W. These rocks have been intruded by (1) pre-Beltian pegmatites now metamorphosed, (2) Laramide pegmatites and minor aplites, and (3) a medium-grained, 30-foot ultramafic dike (probably Laramide) that trends northeast and is vertical. The older pegmatites, which are foliated sills (granulites) and form part of the metamorphic sequence, have been described previously.

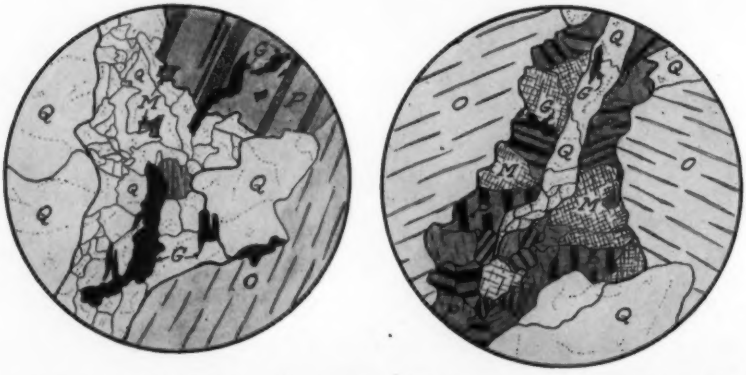

FIG. 8a (left). Quartz (Q)-graphite (G)-muscovite (M) veinlet cutting medium-grained quartz-orthoclase perthite (O)-plagioclase (P) pegmatite, Crystal Graphite mine, southeast of Dillon, Montana. × 28.

FIG. 8b (right). Quartz (Q)-albite (P)-microcline (M)-graphite (G) veinlet cutting quartz-orthoclase perthite (O) pegmatite, Crystal Graphite mine, southeast of Dillon, Montana. Note zoning in veinlet. × 28.

The younger pegmatites lack the foliated texture of the pre-Beltian group, although where they contain partly reworked gneiss inclusions, a rude layering may appear. They contain quartz, microcline, orthoclase, plagioclase, garnet, biotite, graphite, muscovite, chlorite, sericite, and epidote. A little quartz and microcline occur graphically intergrown. Perthitic potash feldspar occurs in generally euhedral 2-inch Carlsbad twins, with interstitial gray quartz. Some 2-inch masses of bright green perthitic microcline were found in one body. Garnet and quartz are graphically intergrown.

Well-defined microscopic veinlets contain albite, quartz, microcline, muscovite, and graphite. The plagioclase of the surrounding pegmatite is Ab 87; that of the veins is Ab 95. Microcline is restricted to veinlets and is probably

hydrothermal in origin. Graphite occurs as plates in and around the veins (Figs. 8a and 8b).

The younger pegmatites strike N. 50–65° E., dip 60–65° NW., and have been intruded chiefly into biotite gneiss and dolomitic marble. A large pegmatite body 800 feet long and nearly 100 feet wide lies just southwest of the marble nose. Aplite dikes are less common and consist of very fine-grained saccharoidal quartz, feldspar, garnet, and graphite. A few quartz veins also are present.

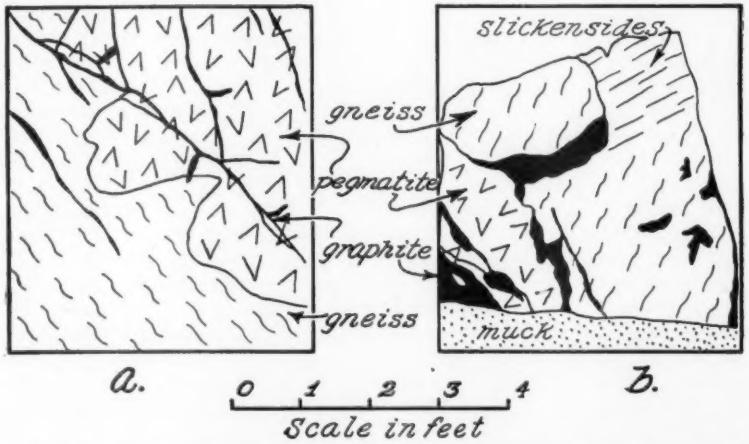

FIG. 9. (a) Veinlets of graphite cutting pegmatite and biotite gneiss in adit at switchback in road. (b) Veinlets and pods of graphite cutting pegmatite and injection gneiss at face of short drift from Antelope adit. Crystal Graphite mine, southeast of Dillon, Montana.

The main graphite veins occur southwest of the dolomite nose, chiefly in gneissic rocks. The mineralized belt, which trends N. 45–65° E. and dips 60–85° NW., consists of a shatter zone 100 to 125 feet wide, extending to the southwest from the marble nose. Graphite occurs in small veins, pods, stringers, and disseminations. Much of it appears to have formed by open space filling along fractures and faults, but some apparently formed by replacement. Individual veins commonly are 1 to 4 inches thick, but some are as wide as 18 inches. Many are 3 to 8 feet long, and a few have been followed for 50 feet. The graphite is in coarse flakes and blades with some fibrous material similar to that from Ceylon. Comb structure is common in many veins; in others flakes lie parallel with the walls; in some a random orientation prevails. In pods rosette structure is well developed. Small scale movements along graphite veins have been facilitated by the lubricating action of the mineral, and slickensided veins are common. Irregularities in detail of individual veins are shown in Fig. 9. Zones of veinlets have a general attitude, but individual

units vary widely in strike and dip. Graphite is closely associated with pegmatite and aplite, but veins and disseminations also occur in biotite gneiss, the chief host rock, quartzite, sillimanite schist, and lime-silicate gneiss.

The genetic relationship of graphite and pegmatite has been emphasized by Bastin (2). Much of the graphite in pegmatites is clearly late and was formed as veins by fluids moving along fractures in crystallized rock. Some disseminated graphite in pegmatite probably formed at the same time as the other magmatic minerals. The veins appear to have formed as the final stage in the process of pegmatite consolidation.

The source of the carbon could be (1) primary C or CO_2 in the pegmatitic magma, (2) graphitic material in the gneisses and schists incorporated by the pegmatitic magma, and (3) carbonate in the dolomitic marble decomposed to CO_2, then to CO and C by the contact action of pegmatite. The second possibility does not seem likely, for the vein graphite is clearly later than the period of regional metamorphism. No persistent lithologic horizons containing disseminated graphite occur; the mineralization cuts across the trend of the rock units.

A few pegmatites are intrusive into marble, but most of the largest ones lie in gneiss. Those in marble are small, and have had minor effect upon their wall rock. The contacts with marble are sharp, and there has been no incorporation of carbonate material by the pegmatites, for mineralogically they are identical with those in gneiss. Graphite is not more abundant, but appears to be somewhat less common in these pegmatites. A few scattered crystals of diopside and phlogopite may persist for a foot from the pegmatite margins. If carbonate had been dissociated by pegmatite to yield graphite, it is reasonable to expect that magnesium-rich silicates would have been formed in abundance, especially since graphite is so very plentiful.

Carbon may well have been a primary element in the pegmatitic magma. Graphite as an igneous accessory mineral is not uncommon. Whether it existed as dissolved carbon or as dissolved CO_2 is a matter for speculation. Winchell (48) has argued for the presence of CO_2 and subsequent deoxidation.

Other Pegmatites.

Horse Creek Quartz-Diorite Pegmatites.—Quartz-diorite pegmatite is exposed in an adit that has been driven into the north valley side a few tens of feet above the road level, at a point 3 miles northeast of the mouth of Horse Creek, southeast of Sheridan, in Madison County. The adit explores a mafic dike that strikes N. 25° E., dips moderately northwest, and is about 35 feet thick. Chromite, clinochlore, and fibrous and massive serpentine form bands in the mafic rock. Other nearby chromite deposits have been described by Jones (14).

The pegmatite, which follows a well-defined fracture, strikes N. 40° E. and consists of two vertical lenses. The first, 6 feet long and 2 feet thick at the center, has a marginal zone of coarse biotite. It consists chiefly of coarse-grained and coarsely twinned white andesine and minor quartz and orthoclase. Coarse graphic plagioclase-quartz also occurs. The second lens, 4 feet long

and 3 feet across, sends several apophyses into mafic wall rock. Coarse-grained andesine and subordinate quartz form a central unit, with borders of fine-grained, gray-brown plagioclase, biotite, and hornblende. Biotite is abundant in thin plates an inch or less wide. Lustrous greenish black hornblende occurs in prismatic crystals, 2 inches or less in length, some of which are rimmed by gray-green actinolite. Other crystals are cut by fine-grained actinolite veinlets normal to their length. Similar actinolite and ¼-inch blebs of calcite replace andesine. Microscopically the marginal pegmatite rock consists chiefly of sericitized andesine (Ab 64) in subhedral to euhedral crystals with about 10 percent of interstitial orthoclase (Fig. 10a). Accessory minerals are garnet in clusters of very minute grains, and enstatite in groups of stubby laths.

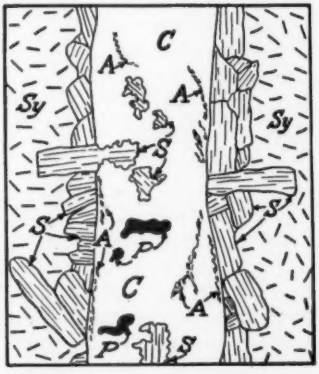

FIG. 10a (left). Subhedral andesine (P) with interstitial orthoclase (M) in quartz-diorite pegmatite, Horse Creek, near Sheridan, Montana. × 26.

FIG. 10b (right). Pegmatite veinlet of sanidine (S) and aegirine (A) replaced almost entirely by calcite (C) and pyrrhotite (P). In syenite (Sy) from Big Sandy Creek vermiculite deposits, Bearpaw Mountains, Montana. × 1.

Mica Creek Peridotite Pegmatite.—An ultramafic pegmatite on Mica Creek, a south-flowing tributary of Squaw Creek, 15 miles southwest of Bozeman, Gallatin County, has been examined by Dr. E. S. Perry. The dike has been intruded into biotite gneiss and hornblende schist. It is vertical, trends a few degrees west of north, ranges in thickness from 10 to 20 feet, and can be traced for 600 feet over a vertical distance of 400 feet. Specimens examined consist essentially of hornblende and biotite in various proportions. A small amount of quartz and feldspar in thin stringers may be later. Hornblende occurs in parallel or randomly oriented blades as much as 3 inches long. Biotite is intergrown with hornblende and appears to replace it along cleavage directions. Parts of the dike consist of almost pure biotite in books ¼ inch to 2 inches across.

PEGMATITES OF TERTIARY AGE.

General.

The main pegmatites of Tertiary age are those associated with small masses of alkalic rocks. The best examples are from the Bearpaw Mountains and near Libby. At the former occur nepheline syenite pegmatites, syenite pegmatites,[10] and complex veins. At the latter are found mafic pegmatites, granite pegmatites, and high temperature veins. The mineral assemblage of the Libby group is characterized by the presence of vanadium and strontium. The Bearpaw pegmatites are marked by relatively high contents of zirconium, strontium, and titanium.

The pegmatites on Gird Creek, east of Hamilton, probably also belong in this age group, but have not been studied in detail. However, the stock there is syenitic and the pegmatites contain coarse melanite. Syenite pegmatites with orthoclase-microperthite, aegirine, sphene, and muscovite have been recorded by Burgess from the Highwood Mountains.[11] The mafic pegmatites near Cooke City (22) are believed to be Tertiary. They contain hornblende, magnetite, apatite, and plagioclase.

Selected Examples.

Bearpaw Pegmatites.—The Rocky Boy stock of alkalic rocks is 6–7 miles south-southeast of Rocky Boy Agency on the Rocky Boy Indian Reservation in Chouteau County. The geology and pegmatites have been described by Pecora (30, 31). The composite intrusive consists of pyroxene-rich rocks, shonkinite, syenite monzonite, and nepheline syenite with unusual nepheline syenite pegmatites. It cuts rocks of upper Cretaceous age and was intruded in early Tertiary time. On and near Pegmatite Peak numerous small nepheline syenite pegmatites crop out. Pecora (30), records the following unusual mineral assemblage: sanidine, nepheline, sodalite, biotite, melanite, sphene, aegirine, eudialyte, lamprophyllite, albite, brookite, zircon, stilpnomelane, catapleiite, and elpidite.

Vermiculite-bearing pegmatites and veins occur on the upper reaches of Big Sandy Creek. They intrude syenite porphyry and fine-grained alkalic monzonite. At least three large and several smaller pegmatites are exposed in the numerous shallow workings. They range in thickness from a few inches to over five feet, are generally vertical or nearly so, and strike from N. 15° W. to N. 30° E. The chief minerals are sanidine, biotite, calcite, pyrrhotite, and pyrite. In addition, the accessory minerals, aegirine, chalcopyrite, galena, and sphalerite were noted, and Pecora (31) has also identified adularia, sphene, zircon, magnetite, ilmenite, hematite, brookite, perovskite, apatite, chlorite, fluorite, barite, celestite, apophyllite, and analcime. He believes the deposits are telescoped and were formed "at a depth of from 3,000 to 5,000 feet under

[10] Pecora, Wm. T., Structure and petrology of the Boxelder laccolith, Bearpaw Mountains, Montana: Geol. Soc. America Bull. 52, p. 833, 1941.

[11] Burgess, C. H., Igneous rocks of the Highwood Mountains. Part IV. The stocks: Geol. Soc. America Bull. 52, p. 1824, 1941.

conditions of rapid fall in temperature." Scales of native copper occur as an alteration product.

Sanidine occurs as blocky crystals in calcite which is usually associated with abundant sulfides and in some dikes is clearly later than the feldspar. In these examples feldspar has been partly replaced by carbonate, and ragged relicts of sanidine remain in a banded aggregate of white to tan calcite blades (Fig. 10b). Aegirine generally is in fine needles in thin streaks or layers that may be concentrated near the margins of a few of the smaller bodies. Biotite, in books 8 inches or less across, is most abundant along the walls of the larger deposits. Books may be arranged normal to the contacts. Locally small vugs occur into which project sanidine crystals and aegirine needles. Pyrrhotite and other sulfides occur in calcite as rounded masses as much as 6 inches across. Pyrrhotite, which is the most abundant, is largely altered to limonite. Biotite is partly altered to hydrobiotite, and some of it has been leached to fragile white plates.

Polished sections of the sulfide minerals show that chalcopyrite has formed later than both pyrite and pyrrhotite. The copper sulfide is concentrated along contacts between pyrrhotite and pyrite or between pyrrhotite and calcite. Thread-like veinlets follow fractures in both pyrite and pyrrhotite. Pyrite forms minute veinlets along cleavages of sanidine, as does calcite. Calcite veins and corrodes all the above sulfides and galena, too. Along cracks in pyrrhotite the formation of marcasite in numerous minute concentric ovules has been initiated. The sequence of formation of these minerals appears to be sanidine, pyrite and pyrrhotite, chalcopyrite, galena, calcite, and marcasite.

Libby Pegmatites.—The Libby vermiculite deposits, which are in Lincoln County in the lower part of Rainy Creek valley, 2 miles above its mouth and 7 miles northeast of Libby, have been studied by Pardee and Larsen (29) and Kujawa (18). Special studies of the rocks and minerals have been made by Larsen and Hunt (20), Goranson (6), Larsen and Pardee (21) and Gruner (7).

Vermiculite and tremolite asbestos deposits have been formed in coarse pyroxenite through the intrusion of syenite. Four types of pegmatite occur in the stock, which transects rocks of the Belt Series: (1) Mafic pegmatites related to the pyroxenite and containing 5-inch diopside crystals, hornblende, perthitic microcline, aegirine, aegirine-augite, and secondary vanadinite. (2) Syenite pegmatites containing perthitic microcline, vanadiferous aegirine, albite, and apatite. (3) A nepheline-syenite pegmatite with albite, nepheline, microcline, aegirine, magnetite, apatite, fluorite, cancrinite, and natrolite. (4) Granitic pegmatites, the youngest intrusives, consisting of perthitic microcline, quartz, and aegirine. High temperature veins that resemble pegmatites contain a quartzose core with chalcopyrite and galena and marginal zones of vanadiferous aegirine, aegirine-augite, microcline, quartz, fluorite, pyrite, pyrrhotite, chalcopyrite, galena, calcite, strontianite, and celestite.

The intrusion of syenite pegmatite into pyroxenite first produced biotite, which was altered subsequently to vermiculite. This abstraction of potash may well have been accompanied by muscovitization in the syenite and was

probably due to the action of later pegmatitic solutions. The vermiculite deposits show no relation to the present water table.

Gird Creek Pegmatites.—A group of pegmatites on Gird Creek, 11 miles east of Hamilton in Ravalli County, are in a small stock (1 × 3 miles) that has intruded Beltian rocks (Newland formation). Dr. E. S. Perry reports that the stock of pyroxenite and syenite is cut by pegmatites, 6 inches to 3 feet wide. Specimens show that fine-grained biotite, partly altered to vermiculite, is associated with pegmatites as irregular masses and also is disseminated in altered pyroxenite. The pegmatites contain oligoclase (Ab 88), green hornblende, apatite, melanite, sphene, and epidote.

UNIVERSITY OF MICHIGAN,
ANN ARBOR, MICH.,
March 14, 1949.

BIBLIOGRAPHY.

1. Barrell, Joseph, Geology of the Marysville mining district: U. S. Geol. Survey Prof. Paper 57, p. 62, 1907.
2. Bastin, E. S., Graphite deposits of Ceylon: ECON. GEOL., vol. 7, pp. 419–443, 1912.
3. Cooke, S. R. B., and Perry, E. S., Columbium and cerium minerals in Montana: Am. Mineralogist. vol. 30, pp. 623–628, 1945.
4. Dunn, J. A., The aluminous refractory minerals; kyanite, sillimanite, and corundum in northern India: India Geol. Survey Mem. 52 (2), pp. 145–274, 1929.
5. Emmons, W. H., Geology of the Haystack Stock, Cowles, Park County, Montana: Jour. Geology, vol. 16, p. 197, 1908.
6. Goranson, R. W., Aegirite from Libby, Montana: Am. Mineralogist, vol. 12, pp. 37–39, 1927.
7. Gruner, J. W., The structures of vermiculite and their collapse by dehydration: Am. Mineralogist, vol. 19, pp. 557–575, 1934.
8. Heinrich, E. Wm., Deposits of the sillimanite group of minerals south of Ennis, Madison County, with notes on other occurrences in Montana: Montana Bur. Mines and Geol., Misc. Contr. 10, 1948.
9. ——, Pre-Beltian rocks near Dillon, Montana: Mineralog. Soc. America, Abstr. 29th Ann. Meet. 1948, p. 7, 1948.
10. Holland, T. H., A Manual of the Geology of India. Economic Geology. Part I—Corundum, pp. 41–42, Calcutta, 1898.
11. Hopkins, J. B., and Taber, John, Bear Trap corundum deposit, Madison County, Montana: U. S. Bur. Mines Rept. Inv. 4039, 1947.
12. Hum, C. K. W., Geology and occurrence of graphite at the Crystal Graphite mine near Dillon, Montana: Montana School Mines, B.S. thesis, 1943.
13. Johnston, G. R., Geology of the Missouri-McKee mines: Montana School Mines, B.S. thesis, 1939.
14. Jones, Verner, Chromite deposits near Sheridan, Montana: ECON. GEOL., vol. 26, pp. 625–629, 1931.
15. Jovik, J. N., Mineral occurrences in certain pegmatite dikes in southwestern Montana: Montana School Mines, B.S. thesis, 1942.
16. Knopf, Adolph, Ludwigite from Colorado Gulch, near Helena, Montana: Am. Mineralogist, vol. 27, pp. 824–825, 1942.
17. Kolesar, J. J., Geology of Lost Creek Canyon with special reference to igneous activity: Montana School Mines, B.S. thesis, 1935.
18. Kujawa, Raymond, Mineralogy and genesis of the vermiculite deposits at Libby, Montana: Montana School Mines, B.S. thesis, 1942.
19. Landes, K. K., Age and distribution of pegmatites: Am. Mineralogist, vol. 20, p. 95, 1935.
20. Larsen, E. S., and Hunt, W. F., Two vanadiferous aegirites from Libby, Montana: Am. Jour. Sci., vol. 36, pp. 289–296, 1913.
21. Larsen, E. S., and Pardee, J. T., The stock of alkaline rocks near Libby, Montana: Jour. Geology, vol. 37, pp. 97–112, 1929.
22. Lovering, T. S., Magmatic chalcopyrite, Park County, Montana: ECON. GEOL., vol. 19, pp. 636–640, 1924.
23. Maguire, Don, Precious stones: Mines and minerals, vol. 20, no. 5, pp. 222–223; vol. 20, no. 6, pp. 255–256, 1899–1900.

24. Miller, Willet G., Corundum and other minerals: Ontario Bur. Mines, Rept. 8, pp. 205–240, 1899.
25. Morozewicz, Jozef, Experimentelle Untersuchungen über die Bildung der Minerale im Magma: Min. pet. Mitt., vol. 18, pp. 215–219, 1899.
26. Nordstrom, C. L., Geology of a kyanite deposit near Ennis, Montana: Montana School Mines, B.S. thesis, 1947.
27. O'Brien, R. D., Gallatin corundum deposit, Gallatin County, Montana: U. S. Bur. Mines Rept. Inv. 4113, 1947.
28. ——, and Taber, John, Bozeman corundum deposit, Gallatin County, Montana: U. S. Bur. Mines Rept. Inv. 4050, 1947.
29. Pardee, J. T., and Larsen, E. S., Deposits of vermiculite and other minerals in the Rainy Creek District, near Libby, Montana: U. S. Geol. Survey Bull. 805, pp. 17–28, 1928.
30. Pecora, W. T., Nepheline syenite pegmatites, Rocky Boy stock, Bearpaw Mountains, Montana: Am. Mineralogist, vol. 27, pp. 397–424, 1942.
31. ——, Telescoped, xenothermal mineral association in alkalic pegmatites and related veins, vermiculite prospect, Bearpaw Mountains, Montana: Am. Mineralogist, Abst., vol. 33, pp. 205–206, 1948.
32. Peoples, J. W., and Howland, A. L., Chromite deposits of the eastern part of the Stillwater complex, Stillwater County, Montana: U. S. Geol. Survey Bull. 922–N, 1940.
33. Perry, E. S., and Cooke, S. R. B., Spectrographic prospecting for beryllium in pegmatites of western Montana: Am. Mineralogist, vol. 31, pp. 499–502, 1946.
34. Read, H. H., On quartz-kyanite rocks in Unst, Shetland Islands, and their bearing on metamorphic differentiation: Mineralog. Mag., vol. 23, pp. 317–328, 1932.
35. Rogers, A. F., On corundum-syenite (uralose) from Montana: Jour. Geology, vol. 19, pp. 748–751, 1911.
36. ——, Baddeleyite from Montana: Am. Jour. Sci., vol. 33, pp. 54–56, 1912.
37. Ross, Clyde P., Eastern front of the Bitterroot Range near Hamilton, Montana: Geol. Soc. America Bull. 58, pp. 1222–1223, Abst., 1947.
38. Rostad, Ora, Pegmatites in southwestern Montana: Montana School Mines, B.S. thesis, 1941.
39. Sahinen, U. S., Geology and ore deposits of the Rochester and adjacent mining districts, Madison County, Montana: Montana Bur. Mines and Geol. Mem. 19, 1939.
40. Seager, G. F., Gold, arsenic, and tungsten deposits of the Jardine-Crevasse Mountain district, Park County, Montana: Montana Bur. Mines and Geol. Mem. 23, 1944.
41. Spaenhauer, F., Die Andalusit- und Disthenvorkommen der Silvretta: Schweizer. Min. pet. Mitt., vol. 13, pp. 323–345, 1933.
42. Sterrett, D. B., Mica deposits of the United States: U. S. Geol. Survey Bull. 740, p. 105, 1923.
43. Stoll, W. C., Preliminary report on mica and beryl pegmatites in Idaho and Montana. Part II: U. S. Geol. Survey, Strat. Minerals Invest., 1945.
44. Stuckey, J. L., Cyanite deposits of North Carolina: Econ. Geol., vol. 27, pp. 661–674, 1932.
45. Tansley, Wilfred, Schafer, P. A., and Hart, L. H., A geological reconnaissance of the Tobacco Root Mountains, Madison County, Montana: Montana Bur. Mines and Geol. Mem. 9, 1933.
46. Weed, W. H., Geology and ore deposits of the Butte District, Montana: U. S. Geol. Survey Prof. Paper 74, p. 37, 1912.
47. Winchell, A. N., Graphite near Dillon, Montana: U. S. Geol. Survey Bull. 470, pp. 528–532, 1910.
48. ——, A theory for the origin of graphite as exemplified in the graphite deposit near Dillon, Montana: Econ. Geol., vol. 6, pp. 218–230, 1911.
49. ——, Mining districts of the Dillon quadrangle, Montana: U. S. Geol. Survey Bull. 574, 1914.

DISCUSSION AND COMMUNICATIONS

ORE AND GRANITIZATION.[1]

Sir: In reply to the recent discussion in this JOURNAL by A. B. Edwards and A. J. Gaskin of the above paper, the following comments are offered:

DISTRIBUTION OF ORE IN GEOLOGICAL TIME.

Thorium.—As stated on p. 481 of the original paper, the aim was to show "only general trends." The fact that there is some monazite associated with the Mesozoic granites of Malaya does not, in the writer's opinion, invalidate the argument; that the monazite is low in thorium content, is interesting; that monazite could be produced is related to the fact that such large quantities of tin-bearing gravel are treated annually. That the production of monazite is small compared with the enormous amounts of gravel treated, seems to indicate a generally low thorium content for the granites of the region.

Tantalum, Tin.—Again, it was not intended to imply that tantalum is not found with tin deposits. The fact that tin and tantalum are found together at Moolyella and at Greenbushes (Western Australia) is well known to the writer who has examined both deposits. Odd associations of this type however are considered quite irrelevant to the argument. Certainly elements of such similar ionic radii and valency are likely to be closely associated. However, a study of the paper by Baker (2)[2] which is an up-to-date and comprehensive compilation, will quickly show that there is a remarkable concentration of tantalum in the Precambrian pegmatites. In contrast, the amount of tin associated with Precambrian granites is relatively small.

The postulate by Edwards and Gaskin that there may be just as much tantalum associated with the Mesozoic granites of Malaya as with those of the producing areas, seems, to the writer, unsound. It is well known that the place to look for new ore deposits is in the vicinity of known high-grade concentrations. It would be more in accordance with experience to expect to find many other low-grade concentrations of tantalum ore in regions where high-grade deposits have been discovered. This is indeed the case in North-Western Australia where tantalum and columbium-bearing minerals may be "panned" from the gravel of creeks occurring over areas to be measured in hundreds of square miles. If gravels of similar quantity to those found in Malaya were available in the North-Western Australian tantalite province, and if water were available for dredging as in Malaya, there is little doubt that the production of tantalite would be very substantial indeed. At the present time, there are considerable yardages of eluvial material carrying 1 to 5 lbs.

[1] ECON. GEOL., vol. 43, pp. 471–498, 1948.

[2] Numbers in parentheses refer to bibliography at end of paper.

tantalite per yard, which, owing to lack of water, have not been worked. The fact that Malaya, in spite of its huge tin production, is not an important producer of tantalite, is considered to be evidence in favor of the thesis presented.

To use production statistics as a guide to the distribution of ore in geological time, is to follow the methods of Niggli (21) whose argument the paper was discussing.

Acid Granites—Tin.—It is difficult to understand the accusation of misconstruing facts when it is stated (p. 476) "Tin is normally deposited at high temperature and at considerable depth, and if the erosion hypothesis were sound, its occurrence in the old formations would be expected. When it is considered that tin is normally associated with acid granite and that Daly has estimated that nine-tenths of the acid granites occur in the Precambrian, this probability would seem to be increased."

Daly's table, quoted on page 474, shows that the Precambrian granites are relatively high in silica and low in calcium and magnesium. Surely, granites showing an accentuation of these features (*i.e.*, so-called "tin-granites") are more likely to occur in Precambrian than in post-Cambrian terrains.

Edwards and Gaskin's criticism is no help in the solution of the fundamental problem posed by Rastall (23) to which the remarks referred and to which an answer had been suggested. Rastall had asked why apparently identical granites introduced tin in some cases and not in others.

Lithophile Element (p. 475).—The statement that lithophile elements are not found associated with "volcanic" activity refers, of course, to the ore-elements mentioned immediately above that statement, *viz.*, U, Th, Cb, V and Be.

Significance of Erosion—Temperature and Depth.—Edwards and Gaskin criticize the logic of the statement (p. 481) that "the evidence presented shows there is but little correlation between the temperature of formation of ore deposits and their distribution in geological time . . ." on the grounds that temperature and depth are independent variables. The references cited show that the argument referred to Niggli's statement (21, p. 48): "In old tectonic units, erosion has destroyed the volcanic and usually, also, the plutonic hydrothermal formations originally present—there remains only the deposits of *high temperature* in the immediate vicinity of the contact zone of plutonic rocks."

The statement does not imply, as Edwards and Gaskin believe, "that high temperature deposits are formed *only* at great depths." It is considered that the statement would be perfectly understood by those familiar with the widely accepted Lindgren classification, though the same, perhaps, cannot be said for Edwards and Gaskin's use of the phrase "high temperature epithermal deposits."

Metallogenetic Epochs and Provinces.—The remarks on metallogenetic epochs and metalliferous provinces generally, constitute an attempt to offer possible explanations for problems posed by Bateman (4) who writes as follows: "The fact of metallogenetic provinces is indisputable but their cause is a problem. Why should the Arizona province be so rich in copper or the Canadian shield province in gold? It cannot be advanced that the Canadian gold province is rich because prolonged *erosion* has cut down to the horizon of a gold zone of mineral deposition. This presupposes a former zonal arrange-

ment, which may or may not have been there, but also presupposes the impossibility that, throughout this great area, all of the deposits, if zoned, had their gold zones at the same horizon. Individual deposits exhibit no evidence of zoning. . . . *The vagaries of erosion and depth of exposure can be eliminated.*"

If the reader assumes, as a starting point, that granites are formed mainly from the crustal material of the earth [3] (in the same way that, in recent years, geologists have normally accepted "magmatic differentiation" as an axiomatic starting point when dealing with ore deposits), it is suggested that it would be possible to explain the occurrence of a gold province, such as the Western Australian province, by assuming that the gold, which is a siderophile element, has been brought into the crust by the volcanic rocks, now greenstones, with which the province is almost co-extensive; it was emplaced into ore deposits during the formation of granite from rocks which included the greenstones. The many similarities between the Western Australian and Canadian provinces suggest that a similar explanation may hold for Canada.

There is a well known, world-wide association between andesites and gold and Malcolm Maclaren (19) thought that "we may have in the auriferous Archaen schists a prototype of the widespread Tertiary andesite." The occurrence of metalliferous provinces may thus be related to the distribution of "source beds." It is hoped to test this hypothesis now that trace-element techniques are becoming increasingly available (24, 18). In this connection, the work of A. Brammall (5) is most interesting. This author found that the Dartmoor granite contains masses of partly assimilated diabase, now represented by hornblendic xenoliths. He found that the diabase was the source of unusual quantities of Ag and Au as well as of the elements Co, Ni, Cr, Sr, Pb and Ir. The following analyses for Ag and Au may be significant:

	Content Grains per ton		No. of samples
	Au	Ag	
"Tor granite." (Apparently considered "magmatic," non-contaminated granite, but, possibly, also, the final product of granitization.)	1.2	21.3	4
Quarry granite ("contaminated").	2.6	46.2	7
Amphibole-bearing pegmatitic hybrid.	64.8	117.9	11
Check assay, biotite from quarry granite.	1.5	108	1

It is not difficult to see that if large quantities of diabase of the type investigated by Brammal were completely replaced by "Tor granite," there would be

[3] A large number of geologists (22) now appear to agree that granite is largely derived from sialic material which has been deeply depressed by folding in geosynclines, though they disagree concerning the processes involved. Many of the postulates in the paper under discussion hold, provided the first principle is correct and do not depend so much on the process of granite-formation.

a considerable concentration of Au and Ag ahead of the front of granitization. This is important when it is considered that diabase is probably equivalent to common basalt, cooled under slightly different conditions.

Recent spectographic analyses of Tasmanian dolerites quoted by Banks (3) indicate that these rocks may contain up to 0.06 percent Cu. A ten-fold concentration of the copper would yield material equivalent in grade to that at present being mined at Mount Lyell, Tasmania.

It is well understood that this does not finally answer Bateman's question, as to why some magmas are rich in copper and others in gold—if he is referring to rocks of sub-sialic origin. It does, however, give an entirely different orientation to the problem and, it is hoped, may suggest new avenues of approach.

Is it not possible, for example, that various groups of abyssal or volcanic rocks come from varying depth within the earth's crust, depending on the depth of penetration of the lines of weakness up which they are forced—hence their varying metal content?

What is the relationship between andesite and gold? Does andesite actually contain more gold than basalt or is it merely a more efficient concentrator of the gold? If the former is true, the view of Shand (26) and others that andesite may be produced by the acidification of basalts by reaction with silicious rocks is interesting because the gold would presumably be derived from acidic rocks. It seems more likely to the present writer, however, that the contamination of basalt by silicious rocks produces a rock, which is capable of concentrating the gold formerly dispersed in the basalt. The special association with andesite of such processes as propylitization, suggests that this may be so.

Basalt, dolerite and gabbro appear to be incapable of concentrating the metals they contain, a fact which may be related to their low water content and high melting points. Basalt, after reaction with silicious sediments to produce andesite, has a lower melting point and probably contains a good deal of water derived from the sediments.

ASSOCIATION OF PARTICULAR ORES WITH SPECIFIC ROCKS.

Collector Mechanism.—In almost all standard literature on ore deposits, the association of particular ores with particular types of granitic rocks has been regarded as indicative of the operation of "magmatic differentiation." The aim of the remarks criticized by Gaskin and Edwards was to show that quite a good case could be made out for an entirely different approach.

The striking similarity in ionic radii and valency of the elements W, Ta, Nb, Sn, Mo, Bi selectively concentrated by acid granites had not previously been considered in this connection.

The norite-nickel association is really quite different from that of the association of particular granitic rocks with particular ores: in the latter case, it is possible that the formation of the granitic rock simply leads to the concentration of metallic elements formerly dispersed in the rocks replaced by the granite; in the former, it is postulated, the nickel was co-magmatic with the gabbro from which the norite was formed by contamination with shales, etc.

Although hesitating to venture into the vexed question of the origin of the Sudbury ores, it is suggested that a different way of looking at granites may throw some light on the subject. The ore is related to the norite but "magmatic segregation" has proved untenable, as an explanation for the origin of the ore (4).

Investigators have found evidence of two periods of "granitic intrusion" between the consolidation of the norite and the formation of the ores, but have been loth to ascribe any genetic rôle to the granite because it is not likely that a granite "magma" would be the source of the nickel: this part belongs to the norite or gabbro. If the granite is viewed as a "concentrator" however, segregating towards its margins, the metallic elements formerly dispersed in the norite replaced—or displaced—by the granite, relationships such as those described for the Creighton and Murray mines (16) would seem to be as expected. The ore occurs at the junction of granite and norite. The granite is the younger rock. The persistent association of the ores with quartz diorite, which, according to Shand (25), is probably a hybrid rock, suggests a zone of contamination towards the contact of granitic rocks with norite or gabbro.

The present author has mapped a somewhat analogous case at Soanesville, Pilbara Gold Field, Western Australia (10). Here, chrysotile asbestos deposits occur persistently along the edges of granitic dikes, cutting peridotites. It could not be suggested that the granite was the source of the chrysotile, but it seems clear that the granite has been important in re-arranging the materials now constituting the chrysotile deposits and has provided water. The presence of considerable quantities of quartz in the Garson mine, Sudbury, is suggestive of the granitic affiliations of the ore.

The fact that, in some instances, the granite appears to have been brecciated prior to the emplacement of the ore, does not necessarily invalidate this idea, because the ore-forming materials and associated volatiles would probably remain fluid for some time after the formation of the granitic rock, allowing time for the brecciation of the latter along its contact with the norite, before the deposition of the ore.

Albite-porphyries and Gold.—The writer's suggestions (pp. 478–80; p. 486) concerning the world-wide association between albite-porphyries and gold deposits were meant as alternatives to "magmatic differentiation" concepts outlined by David Gallagher (11), for example, who states:

> A distinct difference appears to exist between the gold deposits related to albite-bearing rocks and those related to potash-feldspar rocks . . . . The metallogenesis of these gold deposits is not easily explained on the one magma theory of petrogenesis, and it seems necessary to conclude that the granitic and trondhyemitic rock suites, with their respective ore deposits, represent distinct magma types, and in either case the gold mineralizing solutions tended to be *related to the highly albitic differentiates* and left the parental magma shortly after them.

The present author's ideas broadly are:

1. Many albite-porphyries are not intruded as melts, but are replacements. (This seems like a possible solution of the recent discussion as to whether the porphyry of Little Long Lac (6, 24) is a sediment or an "igneous" rock.)

2. Albite-porphyries, in many cases, form above the high-points, or cupolas of granitic batholiths. They appear to represent the upper limits of granitization and it is in these upper regions that volatile materials and those metallic ions not accepted into the crystal lattices of the minerals of the underlying granite, will collect (1). In some instances, the dikes may be regarded as what the writer has called elsewhere (30) "channels of porphyritization" up which the hydrothermal fluids, concentrated above the theatre of granitization, escape. The hydrothermal fluids themselves have small penetrative power and generally require the presence of openings or channelways of some sort before they are able to move.

3. The possibility that gold (Au^{1+}, 1.37) may substitute for potassium (K^{1+}, 1.33) seems to be a good reason for supposing that a soda-rich granitic rock would be an efficient concentrator of gold previously dispersed within the rock replaced by the granite.

These concepts are considered to fit rather well with Gallagher's main generalizations with which, allowing for changes of terminology, the present writer agrees, viz:

(a) The albitic intrusives shortly preceded the mineralization with soda and albite in some cases, extending over into the period of vein formation.
(b) The mineralizing solutions did not come directly from the albitic rock, but both were derived from a common parent magma below.
(c) In some cases, the albitic forerunners exerted a structural control on ore deposition.

Ore and Types of Batholiths.—Edwards and Gaskin's assumption that the view that different types of batholiths may have varying significance regarding the origin of ore deposits involves "serious misconceptions" is considered somewhat gratuitous. The fact that some ore deposits are associated with small stocks—*e.g.*, the porphyry copper deposits of the southwestern United States, is not unknown to most geologists, but to believe that this invalidates the whole argument involves a considerable over-simplification of the problem. Thus, C. D. Hulin (15) has concluded that at Ely, Nevada, and at Grass Valley, California, for example, the mineralization was later than the monzonite stocks and has been derived from some underlying source. The stocks merely provided a suitable structural environment for the localization of the ore. This is similar to the relationship between albite-porphyries and gold described above.

In the Cobar-Nymagee district of N.S.W., the writer, assisted by others, has recently completed reconnaissance mapping, based on aerial photography, of an area of approximately 2,000 sq. miles. The results of this investigation are described elsewhere (30), but briefly, in a regional sense, the ore-deposition (copper and gold) seems to be strikingly related to the distribution of a concordant granitic mass but shows little relationship to the occurrence of the subsequent, cross-cutting, Erimeran granite batholith. In several instances in this district, however, ore deposits are clearly related to granite-porphyry dikes and stocks, which, the regional mapping seems to indicate, probably overlie the high-points or cupolas of non-outcropping portions of the concordant granite mass. In other instances, the ore deposits occur in elongated domal struc-

tures. If the known positions of the concordant granite are projected parallel with the bedding, it is seen that these domal structures, carrying mineralized fields, also probably overlie high-points, or cupolas, in the concordant granite.

At Wrilong, near Nymagee where chalcopyrite ore occurs in two shears situated within a band of porphyry 700 feet wide, samples were cut across the strike of the porphyry and were tested by dithizone (18, 25) for copper content. This reagent is believed to be capable of detecting, under the conditions of the test, the presence of 0.02 part per million of extractable copper; however, only those samples taken in or near the shear zone gave positive tests for copper. These results tend to confirm Hulin's view that the small granitic stocks etc. are not the source of the ore, but tend to localize it; in many instances the ore comes in after shearing or brecciation of the stocks. These findings are similar to those concerning albite-porphyries and gold.

In the Nymagee district, some of the porphyries appeared to be of replacement origin and contain remnants of oriented bedding; in other cases, transgressive plugs of granitic material are closely associated with ore-deposition. The field evidence again indicates, however, that these may have formed largely above the tops of non-outcropping, concordant granite. Following Dunn (7), it is considered that these may have been formed from "magmatized" material, derived from the generally granitized mass below.

Summing up, it may be said that the "hydrothermal fluids" accumulated above a theatre of granitization, have small penetrative power and require the presence of channelways, openings, etc. before they are able to move. "Magmatized" granitic material is much more capable of forcing its way through the roof-rocks, and, in so doing, prepares the way for the accumulated "hydrothermal fluids." Further, it seems likely that, in some instances, "dikes" etc. are formed rapidly by processes which may be called granitization or porphyritization (1), and these also act as channelways of escape. This is the process previously outlined in seeking to explain the relationship between gold deposition and some albite-porphyry dikes.

This evidence is meant to indicate that the argument that ore formation is more closely connected in time and space with the formation of synchronous than of subsequent batholiths, does not necessarily involve "serious misconceptions" because pyrometasomatic ore deposits are commonly associated with transgressive "cupolas" and stocks.

In many instances the time factor in ore deposition is most suggestive, when considered in the light of Dunn's (7) hypothesis concerning the subsequent "magmation" of granitized material. Thus, at Spargo's Reward Goldmine (29), 28 miles south of Coolgardie, the writer found that pegmatite dikes cut the gold-pyrite-arsenopyrite replacement orebodies and seam the surrounding rocks. Obviously the pegmatites are post ore and they have very little effect on the deposits. Ellis (8) noted the same phenomenon in the Yilgarn goldfield, and, partly on this basis, concluded that there were two periods of intrusion, but that both originated in a common "magma chamber."

Matheson and Hobson (20, p. 22), speaking of the same area, state:

> . . . that one period of granitic intrusion could have produced the same results. The granite which is responsible for the auriferous quartz was intruded simultane-

ously with, or subsequently to the folding. The regional granitization of the country was brought about by the intrusive granite . . . .

Numerous instances of pegmatite dikes intruding auriferous quartz reefs, and pegmatite dikes occupying faults which have displaced auriferous quartz reefs, are recorded. Whether or not this is evidence for two periods of granitic intrusion, is problematical.

The present writer ventures the opinion that the conflict of ideas indicated here arises from traditional thinking regarding the origin of granite. The formation of Ellis' migmatites and replacement gneisses probably came first and was accompanied by ore deposition. Subsequent mobilization of portion of this material and its upward movement under tectonic pressure is now evidenced by the intrusion of gold-bearing lodes and reefs by pegmatitic dikes. These dikes are conspicuous by the fact that they do not in any way affect ore deposition, yet all three authors cited clearly believe that there is no large time interval between ore formation and the intrusion of the pegmatites.

At Bendigo, the Harcourt granite, outcropping at the southern end of the field, completely truncates the complicated domal structure in which the quartz-gold deposits occur. It seems most unlikely that the ore originated from the granite while the latter was in its present position, a view shared by J. B. Stone (27) who states:

A mine that is good at one level, is apt to be good at deeper levels, but an adjoining mine may be poor throughout.

This vertical repetition and also the distribution of production in plan make it improbable that the source of the ore solutions was the outcropping Harcourt batholith, but suggest that the source was a separate offshoot of a great underlying regional batholith, and that this offshoot lies below the centre of the district.

The present writer considers that the Harcourt granite, which shows so little relationship to ore deposition, is of the subsequent type and it reached its present position after becoming magmatic. The ore deposits were formed when the actual granitization took place, probably at much greater depth than that at which the Harcourt granite is now found. At the time of ore deposition, the synchronous granite would be roughly conformable to the bedding, and the Bendigo dome would thus correspond to the position of a cupola in the underlying concordant granite. It is postulated that this is the major reason for the localization of the field. This line of thought is considered to be of great significance where explanations are being sought for the origin and localization of mineralized fields or districts related to granitic rocks.

Thus, Harris and Thomas (14) have noted that a large proportion of the Victorian goldfields occur on domal structures. The Broken Hill structure is essentially domal and so is that at Kalgoorlie (13). The present writer has described the relationship between concordant granite, domal structures and ore for the Brocks Creek district, Northern Territory (28) and for the Cobar-Nymagee district, New South Wales (30). To consider the association of ore with domes (generally compressed anticlines with reversals of pitch) purely in terms of "openings," "tension," "elongation," and other empirical structural concepts, is, in the writer's opinion, to miss the basic significance of the relationship which appears to exist between more or less concordant granite, domal structures and ore.

It is probably significant that there is a marked fall in intensity of mineralization away from the top of the crest of the anticlines at Bendigo (9). The ore-forming materials, being volatile, tend to collect over the high-points of the underlying concordant granite. This leads to an expectation of a fall in grade down the limbs of the Broken Hill and the Kalgoorlie domes. It also, naturally, leads to the formulation of ideas as to where other mineralized districts might be found.

It will be seen that on the above tentative concepts, the search for ore becomes somewhat analogous to the search for oil. Metals disseminated in volcanic and sedimentary source rocks are expressed out during the process of granitization (or during consolidation after partial melting) and accumulate above the high points of the granitized or partly molten mass. At the time of accumulation of these ore-forming materials, the granite is, in many instances, concordant with the bedding of the surrounding rocks and domal structures in these rocks, or regions of important anticlinal pitch change may thus be very significant. The escape of the ore-forming materials has already been discussed and their final localization into payable shoots depends on the presence of openings, chemically favorable rock etc.—the usual subject of attention by the mining geologist.

CLASSIFICATION OF ORE DEPOSITS PP. 493-95.

Edwards and Gaskin's criticism of the remarks concerning the tin ores of Mt. Bischoff-Renison Bell, Tasmania, are considered quite reasonable and it seems likely, from their writing, that the ores there are of granitic origin. However, recent regional mapping by private companies throws much doubt on the supposed zonal arrangement of ore in the district though this postulate is relied upon by Edwards and Gaskin.

Though not mentioned by Edwards and Gaskin, it is also desired to record here that intensification and extension, under the direction of the writer, of the mapping in the Cobar-Nymagee district, N.S.W., has demonstrated that the ores there are indeed closely related to granite. Faulted, regional anticlines have been very important localizers of ore but it appears that the cores of these anticlines are replaced by concordant granite. There is no longer any room for "deeply penetrating lines of weakness which have reached sources of metals from below the solid crust." This view arose through confining studies to the Cobar mining field and to a strip extending 10 miles north and 20 miles south of the field. It was in the Nymagee district, some 50 miles south of Cobar, that the most conclusive evidence, concerning the relationship between granitic rocks and the ore deposition of the province, was obtained.

It remains, however, to note again that the granitization hypothesis underlines a probably fundamental difference in genesis between ore deposits related to granitic rocks and those related to volcanic rocks. It suggests that the latter should not be expected to continue at depth into the former and that the separation of these two classes of deposits as proposed by Niggli (21), and by others before him, is quite logical. As Lindgren (17), himself, using somewhat different concepts, has written:

It would seem logical to suggest that the epithermal veins were formed from hot solutions which had their origin in the deep reservoirs where magma was differentiated into various types of flow rocks, and not, like most mesothermal and hypothermal deposits, in batholithic intrusions near the surface.

There is an association between volcanic or abyssal rocks and endogenetic ore elements.

CONCLUSION.

The paper criticized by Edwards and Gaskin was an attempt to deal briefly with some of the major problems of ore genesis and to contribute to what Graton (12) has recently called "the all important standpoint of genetic understanding."

It could not be a "critical and balanced discussion" in the face of the almost universal acceptance of the concept of "magmatic differentiation" as the basis of thought. It had first to be shown that perhaps there are alternative ideas to discuss.

Certainly, the evidence provided is incomplete—it could hardly be otherwise in the space of a short paper dealing with such problems. The aim was to suggest and stimulate, not to offer detailed analyses of all aspects of the various problems.

There has been in mind, also, thoughts similar to those recently stated by C. H. Behre, Chairman of the General Committee on Research of the Society of Economic Geologists:

> The discovery of new techniques and of new mineral deposits turns largely on the acquisition and compilation of data in greater quantity and detail; it depends even more, perhaps, in view of the new data thus becoming available, upon the correct evaluation of these data with minds free from historical prejudices . . . .

The origin and emplacement of granite are as yet incompletely understood as reference to a recent symposium (22) will show. Terms such as "synchronous" and "subsequent," batholiths, may have to be dropped. In some cases, cross-cutting granites may not have moved very far at all, in other cases, the movement may have been vast. Nevertheless, there is a growing opinion that the concept that granite is derived by differentiation from basalt is untenable, and that it is formed mainly from the material deposited in geosynclines, perhaps by direct melting, perhaps by some process of transformation. The main point of the above paper was to show that this involves a very serious re-orientation of thinking for the geologist concerned with metalliferous deposits.

Some of the points made by Edwards and Gaskin provide a useful corrective to unsubstantiated speculation, but much of it is didactic in tone and concerns details; the criticism contributes little to the solution of the broad problems under discussion.

C. J. SULLIVAN.

BUREAU OF MINERAL RESOURCES,
GEOLOGY AND GEOPHYSICS,
CANBERRA, A.C.T., AUSTRALIA.
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BIBLIOGRAPHY.

1. Backlund, H. G., The granitization problem: Geol. Mag., vol. 83, pp. 105–117, 1946.
2. Baker, J. S., World survey of tantalum ore: U. S. Bur. Mines Inf. Circ. 7319, 1945.
3. Banks, M. R., Symposium on geochemistry: Australian and New Zealand Assoc. Adv. Sci. Rept., 1949. (Unpublished.)
4. Bateman, A. M.. Economic Mineral Deposits, John Wiley & Sons, New York, 1943.
5. Brammall, A., Rept. of Centenary Meeting, British Assoc. Adv. Sci., pp. 386–387, 1931.
6. Bruce, E. L., The hardrock "porphyry" of Little Long Lac: Econ. Geol., vol. 41, pp. 282–283, 1946.
7. Dunn, J. A., Granite and magmation and metamorphism: Econ. Geol., vol. 37, pp. 231–238, 1942.
8. Ellis, H. A., The geology of the Yilgarn Goldfield South of the Great Eastern Railway: West. Australian Geol. Survey Bull. 97, 1939.
9. Emmons, W. H., Gold Deposits of the World, pp. 528, McGraw-Hill, New York, 1937.
10. Finucane, K. J., Sullivan, C. J., and Telford, R. J., The chrysotile deposits of the Pilbara and Ashburton Gold-fields: Australia, Aerial, Geol. & Geophys. Surv. N. Australia, Rept. Western Australia No. 54, 1939.
11. Gallagher, David, Albite and gold: Econ. Geol., vol. 35, pp. 698–736, 1940.
12. Graton, L. C., Seventy-five years of progress in mining geology: A.I.M.M.E. Anniv. vol., pp. 1–39, New York, 1947.
13. Gustafson, J. K., and Miller, F. S., Kalgoorlie geology re-interpreted: Econ. Geol., vol. 32, pp. 285–317, 1937.
14. Harris, W. J., and Thomas, D. E., The geological structure of the lower Ordovician rocks of eastern Talbot, Victoria: Roy. Soc. Victoria Proc., vol. 46, pt. 2, pp. 153–178, 1936.
15. Hulin, C. D., Factors in the localization of mineralized districts: A.I.M.M.E., Techn. Pub. 1762, 1945.
16. Knight, C. W., Geology of Sudbury area: Rept. of Royal Ontario Nickel Commission, Toronto, 1917.
17. Lindgren, W., Mineral Deposits, 4th Ed., McGraw-Hill, New York, 1933.
18. Lovering, T. S., Sokoloff, V. P., and Morris, H. T., Heavy metals in altered rock above blind ore bodies, East Tintic District, Utah: Econ. Geol., vol. 43, pp. 384–399, 1948.
19. Maclaren, J. Malcolm, Gold: Min. Jour., London, 1908.
20. Matheson, R. S., and Hobson, R. A., The mining groups of the Yilgarn Goldfield south of the Great Eastern Railway: Western Australia Geol. Survey Bull. 98, pp. 21–22.
21. Niggli, Paul, Ore deposits of magmatic origin; their genesis and natural classification, D. Van Nostrand, New York, 1929.
22. Gilluly, James, Chairman, Origin of Granite, Geol. Soc. America Mem. 28, 1948.
23. Rastall, R. H., The significance of variation in granites: Geol. Mag., vol. 84, pp. 29–32, 1947.
24. Reid, J. A., The Hardrock "porphyry" of Little Long Lac: Econ. Geol., vol. 40, pp. 509–516, 1945.
25. Sandell, E. B., Colorimetric determination of traces of metals, Interscience Publishers, Inc., New York, 1944.
26. Shand, S. J., Eruptive Rocks, 2nd ed., London, 1943.
27. Stone, J. B., The structural environment of the Bendigo Gold-field: Econ. Geol., vol. 32, pp. 867–895, 1937.
28. Sullivan, C. J., The relation of ore-occurrence to general geology, Brocks Creek District, Northern Territory: Australasian Inst. Min. Metallurgy Proc. (in press).
29. Sullivan, C. J., Report on Spargo's Reward Goldmine, N. L.: Bureau Min. Res. Geol. and Geophys., Rept. No. 1947/65. (Unpublished.)
30. Sullivan, C. J., The occurrence of mineralized fields within the Cobar-Nymagee metalliferous province: Australasian Inst. Min. Metallurgy Proc., 1949. (In press.)

REVIEWS

Mining Geology. By Hugh Exton McKinstry. Pp. XIX + 680; figs. 150. Prentice-Hall, Inc., New York, 1948. Price $10.00.

As was to be expected, considering the authorship, *Mining Geology* emerges as a fine book and constitutes a milestone in the progress of the ancient art of ore finding. We have in teaching, as well as in practicing the profession, suffered over-long for the lack of such a book; also, its advent is made more timely because of the pressing need for new metalliferous ore supplies so that we are favored indeed to have it spring from such an experienced and gifted source. An unusually fortunate aspect of this work stems from the fact that in embodying the author's own ideas and philosophy it includes inherently those of his mentors, Lindgren, Graton and McLaughlin, which men in turn have made such great and lasting contributions to mining by means of applied geology.

From a professional standpoint, a book such as this is much the man himself. It embodies the sum total of his experience as well as the thoughts which he has accumulated over the years. Doctor McKinstry's work in this respect is favored. Even in our time, wherein most professional men of standing are widely travelled, the author's record stands out as one of exceptional roundness, for he has visited or worked on nearly every continent and has a first-hand knowledge of many of the great mining districts of the world. Thus, in considering his book the reviewer stands somewhat in awe, yet, fortified by contributions from experienced friends, he dares essay an impartial evaluation and in so doing feels protected from charges of too pointed or savage criticism in the hope that thereby future efforts may be improved.

Possibly the working essence of the volume can be summed in McKinstry's own words, namely, "the geologist has nothing up his sleeve" for certainly this book spreads forth the entire field of mining geology in a most open and revealing manner. It is seldom, indeed, that one runs across a technical work (aside from a handbook) which deals so completely with available matter or includes such a vast range of pertinent references. In the latter respect it may aptly be termed a bonanza.

The author's language is well chosen, varied, and comprehensive. The style is easily readable and punctuated with the characteristic McKinstry humor, which, far from detracting from the points to be made, seems only to emphasize the desirable features. It has the good qualities of a handbook yet does not suffer from characteristics of pedantry and dryness. A charming aspect of this work lies in the apt quotations which begin every chapter. These are most effective—at times humorous, and always pointed. In short, the book is a pleasure to read.

The volume is in four parts, with an introduction of nineteen pages which embraces Doctor McKinstry's working philosophy of the volume, and there is appended a glossary of mining and geological terms of 28 pages. Part I deals with basic information, mapping, procedure for assembling information and putting it into usable form; Part II embraces geological principles of ore search and appraisal; Part III is devoted to exploring for, developing and evaluation of ore deposits, and Part IV describes technological characteristics of ore and methods of beneficiation.

Chapter I, Geological Mapping, displays much common sense in suggestions for geological mapping both for surface as well as underground. Those of us who have served time in underground mapping will agree wholeheartedly with the views on washing walls of mine workings before mapping. Despite the obvious importance, it still seems to take too much effort to educate some managements to a point where they appreciate its value. A matter not mentioned, but equally important, is proper light underground. This is very widely neglected not only for mapping but also for sampling. All too often young geologists are expected to ferret their way through semi-darkness and to map important geological features with a tiny lamp which shows up but a bare few square inches of a complicated and important face. Chapter II is noteworthy for its detailed treatment of sampling. Rightly it stresses that sampling cannot be reduced to rule-of-thumb procedure, but must be executed in conformity with geological principles. Much money and effort could be saved daily if engineers practiced this philosophy, for a large share of channel-sampling on operating mines these days is by rote. It could be many times reduced through intelligent geological direction.

While little quarrel can be made with Doctor McKinstry's outline for underground and surface sampling, experienced men will find his treatment of sludge samples far too detailed, and some of it, unfortunately, pointless. The Top-notchers in drill sampling are now well agreed that lack of geological knowledge and errors in technique contribute more to the failures in a sampling enterprise than do errors in formulae. Highly refined methods of calculating sludge are a hindrance to accuracy rather than a help and divert attention from the main issues, chief of which is the importance of recovering core. In the controversial matter of evaluating a sludge sample wherein the valuable mineral differs in specific gravity from the main mass, there is classification in the return drill water so that with the failure to recover all the drill cuttings there disappears inexorably the validity of the sludge sample. It is fruitless, then, to combine a sludge sample of only 50% recovery with a core sample. As one outstanding engineer says, "Why put bad apples with good?" It is likewise fruitless to consider an idea credited to Moehlman which originated in Rhodesia over 20 years ago, whereby one multiplies a sample by its percentage of recovery. This has no basis in common sense. It merely avoids the issue and plays safe—a practice which is already so often resorted to by geologists as to compel admission that our engineering colleagues are justified in their uncomplimentary remarks on this subject.

Drilling, Chapter III, has excellent coverage. Under Diamond Core Drilling one likes especially the phrase that core should have "perpetual care." How often have we not battled it out with mine managers to protect the company's interests in saving core, and no strutting mine superintendent has any more right to throw away core than he has to destroy the office files.

The section on Churn Drilling by Pennebaker and Richards is outstanding in its completeness and penetrating description. Perhaps, however, an observation on the part of the writer may be permitted here inasmuch as he has never seen these sentiments expressed elsewhere, namely, that some of the credit which we ascribe to the accuracy of churn drill sampling in our western porphyry coppers is misplaced. Actually, many of the deposits sampled had such an even distribution of ore minerals in the mass that even a carelessly taken sample would have yielded a representative result. To some extent this holds as well for core and rotary drilling.

Geophysical Investigations, Section IV, comes in for a well rounded discussion, with some pertinent examples of successes. It is perhaps regrettable that a de-

scription of the most outstanding achievement in magnetic surveying in this country is omitted completely from the book, specifically, the detection of the great Cuyuna Iron Range in Minnesota whose ores are valued in the hundred million dollar class. It might have been as well, also, to have listed some outstanding geophysical failures in view of the fact that they outnumber the successes by several hundred times. However, the author gives good criteria by means of which to evaluate the purveyor of geophysical methods, and, equipped thus, a geologist should be well protected.

Laboratory Methods, Chapter V, is complete, and important is the author's stress that such methods have their proper niche. They are essential, but not all essential. Correlating Data, Chapter VI, is again an excellent one, showing the author's rich experience. The models are especially good and many useful points appear as to size of maps, scales, conventions, samples, and the recording of assay data. The treatment of models and block diagrams excels, while a meaty part of this section deals with interpolation and analysis.

Part II, Geological Principles of Ore Search and Ore Appraisal, is certainly one of the most contributive sections. Herein the author draws on a wide background of first-hand observations in many parts of the globe. In the discussion on Theory it is heartening to find that he emphasizes the uniquely valuable quality of imagination. Most of us these days agree that this is a gift which can be used most effectively in ore search and should be encouraged both in the classroom and in the geological office. In fact, it must be unceasingly fostered if we are to find the ores we need. Whether we believe with Anton Gray that our future needs will be met almost entirely by ferreting out the extensions of known ore bodies in old districts, or whether we fall in with that category of our profession which indulges in more fanciful thinking, whereby we foresee the discovery of entirely new districts, we still have a critical need for more imaginative thinking.

Guides to Ore is an up-to-date discussion of matters vital to mining geologists. Currently, one which will hold most ore seekers as being much in the limelight is the treatment of target rings of alteration. Certainly in our western states these alteration halos have promising possibilities for unearthing new ores. In fact, their past record as exploration successes is impressive at Tintic, Utah, where two properties, one of vast wealth, were discovered by testing below alteration aureoles.

Further in the chapter comes an extended discussion of limonitic alteration and its significance with regard to underlying sulphides. While the subject matter is well covered, one doubts if it is worth such a detailed, exhaustive treatment comprising over 30 pages. These box-works are hard enough to distinguish in the field with a hand lens let alone trying to illustrate them by word pictures. The remainder of Part II is a treatise on structural geology as applied to ore deposits and here Doctor McKinstry excels not only as a practicing mining geologist but also as a teaching scientist. His remarks are clear, while the drawings are well done and apt. It is fortunate that the author has such a comprehensive background to draw on in dealing with such important material. It is well too that he frankly slants his dealing with these problems in a practical way for the solution of mining problems. The length of this chapter is fully excused in consideration of the importance of the subject as well as the author's expertness in this field. It is one of the very best parts of the volume.

Part III deals with applied aspects of geology in mining, and beginning with Field Exploration, Chapter 16, the author covers reconnaissance, concessions and prospecting, while Chapter 17 emphasizes the "weakest link in exploration" and

cites Joralemon's thought that a successful mine depends on a chain of favorable conditions. If one link is weak, then the strength of the others is immaterial. Such concepts are valuable and deserve to be stressed. In the busy lives of mining geologists these days it is essential to be able to detect the weak link from a preliminary office study of information on a prospect thereby saving the time and expense required for a field examination.

Under Acquiring Prospects, the author rightly headlights that a geologist should be trained to advise on business deals on properties, a matter which is too often disregarded in our universities. Those experienced in exploration will welcome, too, Doctor McKinstry's ideas with regard to the development of a prospect in a series of steps. Following this practice is helpful not only in educating one's associates, but also, as a means of conserving the venture capital. He touches on cost of development of properties, remarking that due to the instability of present-day labor and material costs, past records can be of little assistance in prognosticating costs on future operation. The treatment of present values is full of common sense. It is pleasing to note that his Hoskold tables are of sufficient range to satisfy both the conservatives and the liberals. On the whole this part of the volume is of high quality.

In the chapter on geological work at an operating mine the author's advice to geologists is wisdom-packed. In a particularly choice part he abjures the young geologist to learn his proper niche in the mine organization and to cooperate fully with all hands. Chapter 20, Engineering Geology in Mining, is most apropos for practically every sizeable operation these days has important problems falling in this category. The author does well with these subjects save for that of water, and here I think the treatment is incomplete. True, he points out that there is room for a book on water problems in mining, but such an easy disposal is inconsistent with his manner of dealing with other subjects while the importance of this particular problem is such as to compel a more extended treatment. One would like to see further information on methods for country rock drainage, measurement of water table during an attack on an underground water problem, as well as safety measures for handling water underground, which certainly should have considerable geological supervision. Currently, the profession is all too aware of some unfortunate occurrences involving water in deep excavations which might have been avoided with proper knowledge and foresight. And, inasmuch as future mining operations are on the whole bound to go deeper and to have a larger extent of workings at a greater depth thereby involving greater hydraulic head, it is well that the oncoming generation of geologists be made acquainted both with the problems as well as the dangers involved.

In this same chapter Dr. Stanley Tyler discusses subsidence, and McKinstry rock-bursts, in a careful manner stating the problems well. Until the experts have reached the answers to rock-bursts we can expect little more than is given here. The chapter on writing and reading reports again shows the author's wide professional range. He will have unanimous support in laying emphasis on good reports. After all, most examinations are made primarily in order to convey one's conclusions in a report which constitutes the sole means whereby one's principals appraise the enterprise. Also, it is wise to remember that a report provides a long-lived basis for judgment of its author.

In a work such as this it seems fitting to include short chapters on ore treatment as well as marketability of metals and ores, which concludes the volume save for unusually complete appendices on classification of rocks, genetic classification of ore deposits, geologic time scales, chemical elements, weights and measures, and

a few other of the more commonly used trigonometric tables, ending with a glossary of mining and geological terms.

Any fair review of a book compares it to similar volumes, but this work is almost unique. The only other comparable effort is Forrester's "Field and Mining Geology," which where it treats of the same material is of high quality, indeed. Yet, in a careful appraisal, McKinstry's book has a wider coverage and excels perhaps by the measure of his world-wide study and far-flung experience.

To sum it up, the writer feels that this volume is above all a helpful work. Those of us who deal in the practical problems of mining geology realize only too well how little real data we have at hand to conjure with, yet we are kept painfully cognizant of how much is demanded in the way of prognostication. Hence, Hugh McKinstry's book is more than welcome, for in it he has documented all essential information which is prerequisite to a consideration and appraisal of the geological problems connected with the search for and mining of epigenetic ore bodies. While neither Doctor McKinstry nor anyone else can think for us, nevertheless in the tangled problems of mining geology he can and has pointed the way to the paths of straight thinking and right practice. This book stands on its own merits as a fine piece of craftsmanship in geology applied to mining, and fully earns a place on the economic geologists' shelves along side the classic volumes of such illustrious predecessors as Hoover, Kemp, and Lindgren.

D. M. DAVIDSON

MINNEAPOLIS, MINNESOTA,
May 11, 1949.

Arabian Oil. America's Stake in the Middle East. By RAYMOND F. MIKESELL AND HOLLIS B. CHENERY. Pp. 201; tbls. 19; appendices 3. The University of North Carolina Press, Chapel Hill, 1949. · Price, $3.50.

This welcomed book is the product of the joint authorship of Raymond F. Mikesell, Professor of Economics at the University of Virginia, and during the war Government Economist in the Middle East, and Hollis B. Chenery, formerly a petroleum engineer, now teaching Economics at the Massachusetts Institute of Technology and writing his Doctor's Dissertation in Economics at Harvard.

Students of international petroleum economics will find well documented information in this book as well as clarifying accounts of oil production in the Middle East, the interests of America and other countries, the impact of oil on the Arabian economy, the effect of Middle East oil on the foreign policy of the United States, future prospects and recent developments.

Three appendices add valuable information to international petroleum economics, useful statistics, and historical documents of agreements.

It will have a strong appeal to executives, economists, petroleum geologists and engineers, and an equally strong appeal to statesmen dealing with international questions arising out of reserves and production of oil in the Middle East.

M. M. LEIGHTON.

Klockmann's Lehrbuch der Mineralogie, 3rd Edit. Revised by PAUL RAMDOHR. Pp. 674; figs. 606; tables. Ferdinand Enke Verlag, Stuttgart, 1948. Price, bound, D.M. 50.

The third edition of this well known work printed in Berlin appeared in December, again revised by Ramdohr. Its form and contents are about the same as its predecessors but it has been brought up to date, particularly with respect to

newer developments in atomic and crystal structure and the clay minerals.

Part I deals with Symmetry, Crystallography and Crystal Structure which is revealed by X-ray; Atomic Radii Behavior under Polarized Light; The Elements and the Periodic Table; Isomorphism; Unmixing Minerals and Ore Formation; and Paragenesis. Part II, the Treatment of Systematic Mineralogy.

The book reflects the careful investigation of the literature by Professor Ramdohr and is a worthy successor to its predecessor.

Heat Conduction, with Engineering and Geological Applications. L. R. INGERSOLL, O. J. ZOBEL AND A. C. INGERSOLL. McGraw-Hill Book Co., New York, 1948. Price, $4.00.

The authors state that this volume is the successor to the earlier and larger volume on *The Theory of Heat Conduction* and that this volume contains, with revisions, considerable of the material of the older book. Less stress has been laid on mathematical phases and more on practical applications, particularly for geologists, geographers, and engineers. Emphasis is laid on graphical methods with simple mathematics.

The subject matter consists of analyses of the steady and periodic flow of heat in one and several dimensions, linear flow, Fourier series, the formation of ice, and methods of measuring thermal conductivity constants. These subject headings deal with refrigeration, insulation, power development, geysers, engine cooling, thawing of soils, cooling of lava and of the earth, frozen soils, post-glacial time calculations, and many other phases in which heat conduction is involved.

The book is still a bit mathematical for the general scientific reader but the many practical applications are digestible and valuable for geologists.

Physical Geology and Man. By KENNETH K. LANDES. Pp. 414; figs. 164. Prentice-Hall, Inc., New York, 1948. Price, $6.00.

This book is planned by the author as a first term textbook of a two-term course in Physical and Historical Geology and relates entirely to Physical Geology. The book is made up in four parts.

Part I is a brief introduction relating to the Science of Geology and the Earth Materials. Part II, Geologic Processes, contains the usual chapters found in physical geology textbooks, namely Work of the Atmosphere, Ground Water, Running Water, Ice as a Geologic Agent, Direct Action of Gravity, Oceans and Lakes, Sedimentary Rocks, Vulcanism and Igneous Rocks, Diastrophism and its Effects. Part III consists of one chapter only on the Earth's Interior. Part IV, Practical Applications, consists of the Search for Mineral Deposits and Geology in Engineering Projects.

The book is nicely printed on good paper which reproduces well a number of excellent photographs, many of which are aerial photographs; there are also a number of fine drawings by John Jesse Hayes. The book should find a place for a first term course in physical geology.

Geology and Man. By KENNETH K. LANDES AND RUSSELL C. HUSSEY. Pp. 518; figs. 188. Prentice-Hall, Inc., New York, 1948. Price, $6.45.

This book, designed by the authors as a textbook for a one-term course in Geology, is a combination of Physical and Historical Geology, with 2 chapters relating to Mineral Deposits and Engineering Geology.

It is identical with "Physical Geology and Man," with the same subject matter and illustrations, except that for Part IV there are added four chapters on Historical Geology dealing with the Origin and Age of the Earth, the Study of Earth History, the History of Life on the Earth, and the Geologic Story of the Earth, taken up by eras. Part V of this volume is identical with Part IV of "Physical Geology and Man." It includes more excellent drawings by John Jesse Hayes.

This volume, as well as "Physical Geology and Man," tends to emphasize the effects that geological processes, both past and present, have had upon mankind. For a one term course covering the entire field of geology this volume looks interesting.

BOOKS RECEIVED.

ALAN T. BRODERICK.

U. S. Geological Survey—Washington, D. C., 1947–1949.

Prof. Paper 215. Geology of the Southern Guadalupe Mountains, Texas. PHILIP B. KING. Pp. 183; pls. 23; figs. 24. *Area is key to study of Marine Permian of West Texas and New Mexico.*

Bull. 944–C. Geology and Ore Deposits of Boise Basin, Idaho. ALFRED L. ANDERSON. Pp. 201; pls. 39; figs. 2. *Two groups of deposits; early Tertiary (?) quartz-gold fissure fillings and early Micocene base metal, gold, silver fissure fillings and lodes. Most of area's production has been from placers.*

Bull. 954–E. Manganese Deposits of the Talamantes District near Parral, Chihuahua, Mexico. I. F. WILSON AND V. S. ROCHA. Pp. 25; pls. 6; figs. 1. *Tertiary brecciated faults filled with 20–30% Mn, .5–1.5% WO_3, barite, probably from ascending solutions. Picking increases grade to 40–44% Mn with considerable loss in reject. Inferred reserves 100,000–125,000 tons 20–30% Mn.*

Bull. 954–F. Manganese Deposits of Mexico. PARKER D. TRASK AND JOSÉ RODRÍQUEZ CABO, JR. Pp. 106; pl. 1; tbls. 17. *Fissure fillings and wallrock replacements. Total inferred ore, 1,500,000 tons, half 30% Mn, half 42% Mn.*

Bull. 959–D. Geophysical Abstracts 135, October-December 1948. V. L. SKITSKY AND S. T. VESSELOWSKY. Pp. 125.

Bull. 960–A. Barite Deposits of Camamú Bay, State of Bahia, Brazil. A. J. BODENLOS. Pp. 33; pls. 8; figs. 3; tbls. 3. *696,300 metric tons 89.5% $BaSO_4$ measured, indicated, inferred. Ore is replacement of Cretaceous arkose bed. Maximum thickness 4.3 meters. Nearby island shows 2900 meters of barite outcrop, probably contains additional large reserves.*

Bull. 960–B. Antimony Deposits of Soyatal District, State of Queretaro, Mexico. DONALD E. WHITE. Pp. 51; pls. 11; figs. 4; tbl. 1. *Third largest Mexican antimony producer (25,000 tons Sb up to 1943). Ore occurs as replacements of or fillings in Lower Cretaceous limestone near faults and fissures, underneath shale, along anticlines.*

Bull. 960–C. Geology of Tungsten Deposits in North-Central Chile. JAMES F. MCALLISTER AND CARLOS RUIZ F. Pp 17; pls. 7; figs. 3. *Moderately high-temperature replacements of post-Mesozoic diorite along joints and faults. Small, high-grade scheelite pods mined.*

Bull .960–D. Tin-Bearing Placers near Guadalcázar, State of San Luis Potosí, Mexico. CARL FRIES, JR., AND EDUARDO SCHMITTER. Pp. 39; pls. 6; fig. 1; tbls. 6. *Large alluvial fans around post-Cretaceous porphyritic granite stock contain .0084% Sn, .0015% Hg; 9.44 grams Ag and .058 grams Au per metric ton. Tests show that if 1946 prices of Sn and Hg doubled and if sufficient water could be found, deposits could be worked.*

Bull. 960–E. Geology of the Huahuaxtla Mercury District, State of Guerrero, Mexico. DAVID GALLAGHER AND RAFAEL PEREZ SILICEO. Pp. 34; pls. 3; figs. 3. *300,000 kg. Hg produced since discovery in 1923. Cinnabar replaces and fills fault breccia in Upper Cretaceous limestone. Ore still persists at depth. No reserves estimated.*

Atomic Energy Development, 1947–1948. U. S. ATOMIC ENERGY COMMISSION. Pp. 213; numerous figures, photos. U. S. Government Printing Office, Washington 25, D. C. *A thorough report written for the layman, covering the development of atomic energy in the U.S.A. This report starts with uranium ores as delivered from the mines, so contains no geology.*

Metal Statistics 1948. Pp. 848. 41st Annual Edition. American Metal Market, New York, N. Y., 1948. Price, $2.00.

North Dakota Geological Survey—Grand Forks, 1948–1949.

Twenty-Fifth Biennial Report. WILSON M. LAIRD. Pp. 16; fig. 1.

The Sodium Sulphate Deposits of Western North Dakota, A Progress Report. IRVING G. GROSSMAN. Pp. 66; maps 16. *Description of previously known and possible new deposits. Apparently large reserves. Possible sources are Fort Union bedrock, glacial overburden. Salts occur in lowest lakes in areas of interior drainage.*

Oil and Gas Map of Illinois. ALFRED H. BELL, DAVID H. SWANN, VIRGINIA KLINE, AND WAYNE F. MEENTS. Illinois State Geological Survey, Urbana, Jan. 1948. *Scale, 1" = 8 miles.*

Chemical and Petrographic Studies of the Fort Hays Chalk in Kansas. RUSSELL T. RUNNELS AND IRA M. DUBINS. Pp. 36; tbls. 8; figs. 6; pl. 1. Kansas Geol. Survey Bull. 82, Pt. 1, Lawrence, 1949. *Enormous tonnages of this Cretaceous chalk are available. Study shows it to be suitable for whiting in the paint, rubber, putty and chemical industries.*

Review of the World Tin Position, 1947–1948. INTERNATIONAL TIN STUDY GROUP. Pp. 32. The Hague, 1948.

Handbook of Uranium Minerals, A Practical Guide for Uranium Prospecting. JACK DEMENT AND H. C. DAKE. Pp. 96; numerous tables, photos.

The Australian Mineral Industry, Economic Notes and Statistics. Vol. 1, No. 1. Pp. 21. Bureau of Mineral Resources, Victoria, Australia, 1948. *First issue of a new publication containing a mineral-by-mineral listing of Australian production.*

Instituto de Tecnologia Industrial—Belo Horizonte, Brazil, 1948.

Bol. 3. Recorrência de Mineralização em Depósitos Calendonianos. CAIO PANDIÁ GUIMARAENS. Pp. 51; pls. 10. *Recurrence of mineralization in Caledonian deposits.*

Bol. 6. The Zirconium Ore Deposits of the Poços de Caldas Plateau, Brazil, and Zirconium Geochemistry. D. GUIMARÃES. Pp. 36; tbls. 6; figs. 4, pls. 7.

Bol. 7. Enstenitization in the Palisade Sill Diabase and its Consequences. D. GUIMARÃES AND B. BRAJNIKOV. Pp. 30; pls. 5; figs. 2.

Preliminary Report on the Linklater Lake Tin Discovery, District of Thunder Bay. E. O. CHISHOLM. Pp. 6; figs. 3. Ontario Dept. Mines Prel. Rept. 1948–11. *Narrow, discontinuous felsite dikes in a 1500′ × 50′ zone carry some cassiterite. Deposits are low grade, but further exploration is warranted.*

The Mining Industry of the Province of Quebec in 1946. Pp. 162; numerous tables. Quebec Dept. Mines, Quebec, 1948.

Memorie e Note dell'Instituto di Geologia Applicata dell'Università di Napoli. Pp. 145; numerous figures, photos. Napoli, 1948. *First volume of a new bulletin which contains 8 separate papers on geologic subjects.*

Geology and Mineralization of the Suian District, Tyôsen (Korea). The Geology of the Suian Gold Mining District. TAKEO WATANABE. Pp. 303; figs. 12; tbls. 14; pls. 41. Sapporo, Japan, 1943. *Pyrometasomatic Au, Cu, Bi and mesothermal replacement Au, Cu, Ag, Pb, Zn deposits in marble near granite.*

Geology of North, West and Central Njombe District, Southern Highlands Province. G. M. STOCKLEY. Pp. 70; pls. 11; maps 2. Tanganyika Dept. of Lands and Mines, Geol. Div. Bull. 18, Dodoma, 1948. *Area contains over 1200 million long tons of magnetite in seams of from 30 to 600 feet wide in gabbro; small pods of chromite in serpentine; traces of platinum, gold, copper and manganese.*

SCIENTIFIC NOTES AND NEWS

G. S. HUME, Chief of the Geological Survey of Canada, has been promoted to Director of the Mines, Forests and Scientific Services Branch.

The Virginia Military Institute, through the department of geology, announces its willingness to become a repository of essential geologic records. This action has been taken in recognition of the need for a decentralization of geologic material A limited amount of space exists at the Preston Library, V. M. I., for such deposition, but the Institute wishes to go on record as being willing to accept such documents as bulletins, monographs, etc., for safekeeping. The essential feature is to serve to decentralize valuable records and hence minimize the risk of total loss by fire or other catastrophe.

ALAN F. MATTHEWS, editor of the U. S. Bureau of Mines *Minerals Yearbook* and author of the *Yearbook's* chapter on uranium and thorium, recently delivered a lecture on uranium and thorium industries supporting atomic energy at the School of Mines, Columbia University, as part of the minerals economics course.

The Geological Society of America, Cordilleran Section, held its 50th Meeting at Berkeley, California, April 14–16, in conjunction with the Paleontological Society, Pacific Coast Branch, and the Seismological Society of America. On April 14 a field excursion was taken to show the general geologic features of the San Francisco Bay area, particularly the features along the San Andreas rift in Marin County.

HOWLAND BANCROFT, who spent the last 18 months in South and South West Africa with headquarters in Tsumeb, has returned to the United States where he will carry on an investigation before returning to South Africa.

HARVEY S. MUDD, president and managing director of Cyprus Mines Corporation, received the Egleston Medal, awarded annually by Columbia University Engineering School Alumni Association, on April 28, for distinguished engineering achievement.

BAILEY WILLIS, emeritus professor of geology at Stanford University, died February 19 in Palo Alto, California, at the age of 91. An internationally known seismologist and geologist, a member of the National Academy of Sciences, author of several important books, and the Winner of many honors and decorations, Dr. Willis had been head of the geology department at Stanford from 1915 until his retirement in 1922.